

Physics of Light Propagation in 3D-Printed Transparent Polymers: A VOSviewer Mapping of Global Research

Ishaan Shanker

Bombay Scottish School, Mumbai. IshaanShanker007@gmail.com

Abstract: Optics through 3D-printed transparent polymers represents an exciting frontier in AM optics, but the world of 3D transparent polymer optics has yet to be explored. In this paper, the authors take a systematic overview of the global scientific and technological research on the physics of light scattering, transmission, and refractive effect in 3D printed optical-grade polymers from simple printed lenses to highly complex integrated photonic components, such as waveguides and biosensors. A mixed-method approach was used, which included systematic literature analysis in Scopus, Web of Science and IEEE Xplore, and bibliometric and co-occurrence keyword mapping with the VOSviewer software. The analysis shows the various optical bottlenecks that have hindered industrial adoption of layer-by-layer fabrication such as high surface roughness values of 30-110nm values ranging from 30-110 nm and refractive index anisotropy. However, there are substantial innovations in terms of manufacturing technologies in the printing of the polymers. Various case studies in the paper investigate how printing parameters, layer thickness, print orientation, photopolymer composition, and curing strategy control the optical anisotropy and the transmission uniformity which are both bottlenecks that need to be mitigated. To contextualize laboratory findings within aerospace and precision optics requirements, quantitative performance metrics including transmission efficiency, scattering loss, and spatial resolution are triangulated against secondary industrial benchmarks sourced from NASA, Statista and McKinsey. After evaluating the findings we see that multimaterial printing and microstructure engineering are the best ways to minimize optical diffusion and to get silica class performance. This work serves as a bibliometric and physical foundation for advancing integrated photonics fabricated via additive manufacturing.

Keywords: 3D-printed transparent polymers; light propagation; optical scattering; refractive index anisotropy; VOSviewer bibliometric analysis; additive manufacturing optics; integrated photonics.

1. Introduction

Additive Manufacturing (AM), commonly referred to as 3D printing, has completely transformed the industrial world from a tool used for prototyping to a key method in manufacturing complex functional parts. The transformative journey started in the 1980s with the invention of stereolithography (SLA) by Charles Hull in 1986, where physical objects were created by adding layers, one by one, from a digital 3D model, instead of subtractive machining (Beníček et al., 2024).

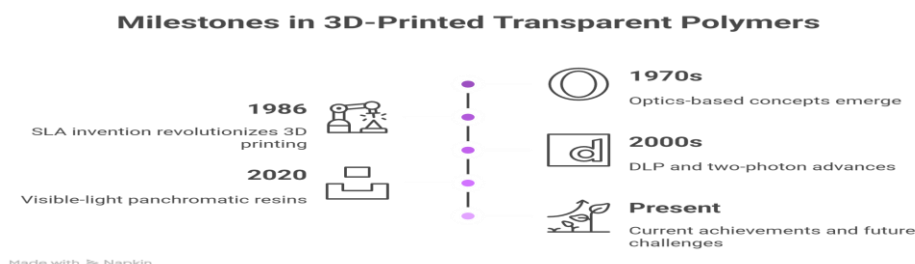


Figure 1. Milestones in 3D-Printed Transparent polymers

Unlike conventional methods like milling, etching or drilling, AM creates complex shapes by printing material on a localized basis in the form of volume elements called voxels. The control of light propagation in these printed structures has evolved from an academic curiosity to a critical need in today's world of optics, enabling significant progress in imaging, sensing, communications, and quantum technologies (Beníček et al., 2024). Transparent polymeric media have become a disruptive, lightweight, and design flexible alternative to traditional glass and crystalline optics, creating new opportunities for integrated and miniaturized photonics. Figure 1 shows the journey and improvement in the manufacturing of 3D Printed polymers from the 1970s to the present day. Achieving optical-grade performance in printed polymers requires a deep synthesis of breakthroughs in physics, chemistry, and laser science (Somers et al., 2023b). Light-driven 3D printing, including techniques such as Digital Light Processing (DLP), Two Photon Polymerization (2PP), and Tomographic Volumetric Additive Manufacturing (TVAM), relies on electric-dipole-mediated interactions between photons and dedicated photo initiator (PI) molecules. In traditional SLA and DLP systems, high energy ultraviolet (UV) or violet light is utilized to trigger photocuring, a process involving initiation, propagation, and termination steps that transform liquid resins into solid networks (Somers et al., 2023b). However, the reliance on UV light introduces significant bottlenecks, including material degradation, occupational safety risks, and limited biocompatibility. Recent chemical innovations have shifted the research focus on visible light (VIS) photocuring. Visible light offers superior depth of penetration, reduced scattering, and compatibility with biological compounds (Ahn et al., 2020). A landmark development in this area is the identification of the photo initiator diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide (DPTBP), which, while originally designed for UV, exhibits sufficient absorption up to 420 nm to generate radicals under visible light. This has led to the formulation of "UVIStar" resins (DPTBP/PETA/HDA), which afford unprecedented transparency and mechanical hardness, rivaling consumer-grade plastics (Ahn et al., 2020). Furthermore, the incorporation of azo-dyes as opaquing agents (OA) has been identified as a critical factor in enhancing spatial resolution by confining curing to specific irradiation zones and widening the processing window.

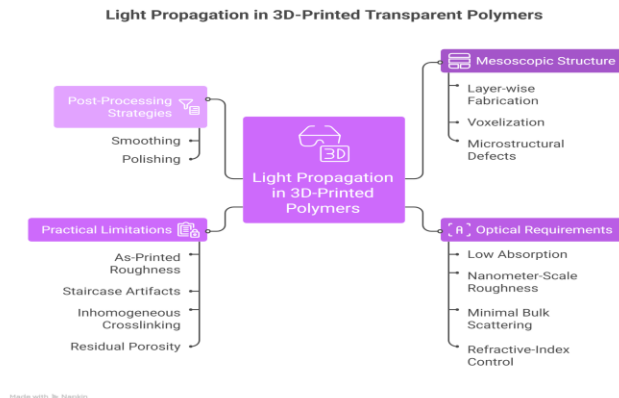


Figure 2. Light Propagation in 3D-Printed Polymers

Figure 2 summarizes the practical limitations, post processing strategies, mesoscopic structural elements, practical limitations and optical requirements associated with the fabrication of transparent 3D printed polymers. The main challenge of 3D-printed optics is moving from process-centric optics manufacturing to physics-centric propagation analysis (Salas et al., 2023). A 3D-printed polymer is not an ideal homogeneous material, but rather a mesoscopic structure with defects that are inherent in the process of layer-wise construction and voxelization. The layered structure leads to a "staircase effect" and surface waviness, especially when elements such as lenses and mirrors require extremely flat surfaces for operation. Such structural features directly affect the propagation of light in terms of phase, amplitude and polarization (Salas et al., 2023). Optical diffusion or light scattering is caused by

internal inhomogeneities like residual porosity, microstructural defects and inhomogeneous crosslinking. The results show that the surface roughness in the range of 30-110 nm is enough to significantly blur the image, while the traditional glass optics usually have a surface roughness of 5-10 nm (Hamp et al., 2021). In addition, the direction of the print line in relation to the incoming light gives rise to anisotropic optical effects, which allows to tailor the light distribution of the diffusive pattern to specific applications such as seasonal solar control for building facades (Hamp et al., 2021). In order to overcome these physical limitations, researchers are investigating post-processing methods like meniscus coating and solvent vapor treatment that have decreased roughness to less than 7 nm. A systematic quantitative analysis is needed to assess the direction of this fast-changing field (Deng et al., 2019). Tools such as VOSviewer and CiteSpace can be used to visualize research network structures, helping researchers to determine the most central authors, institutional centers, and new research frontiers. Based on the analysis of the related fields, scientific research is generally in three stages: preliminary conception, rapid development, and stable in-depth stage (Deng et al., 2019). Amongst the 3D-printed polymers, the USA, China, and Germany stand out as key countries, with the Chinese Academy of Sciences and Wageningen University being the leaders of high-yield production. The field is shifting from just “additive manufacturing” to more comprehensive themes, such as “freeform optics”, “micro-optics”, and “refractive-index control” (Ren & Ju, 2023). New words are beginning to appear, including “burst words” like “ecosystem service” and “active sensing,” which signal a trend toward multifunctional and sustainable photonic systems. Nevertheless, although the publications have increased, the primary authors’ team is relatively dispersed, highlighting a significant need for better cross-national and inter-institutional collaboration (Ren&Ju,2023).

The main objective of this paper is to connect material science and fundamental optical physics in the light of the global research trends. Despite the unprecedented Design-for-Manufacturing (DfM) freedom of AM, there are still physical limitations to achieve high precision components, such as Rayleigh/Mie scattering, material shrinkage, and surface roughness (Blachowicz et al., 2021b). This study employs VOSviewer to visualize the global research network and pinpoints technological milestones and material innovations, including hybrid polymers and two-photon polymerization, towards bringing 3D printing from the macroscale to the nanoscale (Blachowicz et al., 2021b). This mapping will help researchers navigate the challenges of light-matter interactions and structural defects, with the ultimate goal of 3D-printed polymers outperforming or even matching optical materials in miniaturized optoelectronic devices and quantum photonic circuits. This study is designed to systematically analyze the light propagation through 3D-printed transparent polymers from the physics point of view, to understand the major breakthroughs in light scattering, light transmission, and the development from the single 3D-printed transparent polymer lenses to integrated 3D-printed transparent polymer optical components like waveguides and sensors. The analysis will establish a baseline on physical limitations such as surface roughness (30-110nm), refractive index anisotropy, and optical diffusion caused by scattering in functional 3D-printed optics and identify avenues to improve them for multimaterial printing and to reduce optical diffusion, laying the groundwork for innovations in integrated photonics. This study aims to systematically analyze global research trends in the physics of light propagation through 3D-printed transparent polymers, identifying key milestones in light scattering, transmission, and the evolution from standalone lenses to integrated optical systems such as waveguides and sensors. By benchmarking physical bottlenecks like surface roughness (30–110 nm), refractive index anisotropy, and scattering-induced resolution limits, the analysis will highlight pathways for advancing functional 3D-printed optics toward multimaterial printing and reduced optical diffusion, serving as a foundation for innovations in integrated photonics.

2. Literature review

Understanding the interaction of light with solid materials is essential for designing and building complex optical systems. The fundamental principles governing the behaviour of light in solids can be understood by examining the theoretical underpinnings of electromagnetism, i.e., Maxwell's Equations. These equations describe the propagation of electromagnetic (EM) waves in both vacuum and solid-state media (Beckers et al., 2016). Electromagnetic waves consist of two orthogonal vector fields: electric field E and magnetic field B . When an EM wave propagates through a solid medium, it interacts with the dipoles (i.e., polarization) and magnetization of the material. The response of the material to the incident EM wave determines how efficiently energy can be transferred

through the material. The process of transferring data or signals through waveguides occurs at the boundaries between different regions and is described mathematically using Snell's Law and the principle of total internal reflection (TIR)(Beckers et al., 2016). Both principles provide the geometric and mathematical framework necessary to design waveguides with the greatest possible efficiency. However, the physical behavior of 3D printed optical systems is generally limited by the presence of scattering events. Specifically, Mie and Rayleigh scattering are common types of scattering events that occur when there are inhomogeneities and/or structural defects in the solid medium (Bhagyaraj et al., 2020). Both types of scattering events result in a degradation in the clarity and intensity of the light passing through the system. Anisotropy in the solid medium, e.g., birefringence and dispersion, must also be considered to create high-performance optical components. Researchers have begun to explore the use of polymers to create novel composite materials and to develop new functionalization techniques that enable polymers to be reliable candidates for modern optoelectronics (Bhagyaraj et al., 2020). Therefore, the conceptual layer of this paper emphasizes that, although polymers offer many benefits, including their low dielectric constants and mechanical flexibility, to overcome the current limitations in performance, it is necessary to master the underlying physics.

Additive manufacturing, also known as 3D printing, has evolved from being a rapid prototyping technique to being a viable method of producing complex three-dimensional objects across scales ranging from the macroscopic to the nanoscopic (Lee et al., 2013). Unlike subtractive machining, where material is removed by a tool to create a desired shape, 3D printing uses light to add material to a growing object, layer by layer, starting from a liquid “ink”. There are several modes of operation available today that approximate an ideal exposure scheme, where a 3D pattern of light is projected onto the liquid ink and it is cured instantaneously. In all cases, the precision of these methods is determined by the interaction between light and matter mediated by electric dipoles, where photo initiator molecules undergo photoinduced polymerization upon absorbing one photon or multiple photons (Lee et al., 2013). The type of printing technology employed is the most important factor influencing optical resolution and surface quality. Although fused deposition modeling (FDM) is accessible to a wide range of users, it typically results in poor z-resolution and surface waviness that require additional post-processing, such as polishing. On the other hand, stereolithography (SLA) and digital light processing (DLP) offer higher resolutions of approximately 30 to 70 microns (Somers et al., 2023). In DLP and masked stereolithographic apparatus (MSLA), entire layers are cured at once, making these technologies faster than the point-by-point curing of SLA. Currently, the highest resolution is achieved through two-photon polymerization (2PP) and direct laser writing (DLW), which can create features that are smaller than 1 micron and as small as 0.085 microns. However, despite advances made in methodologies, an ongoing methodological challenge exists: to increase the number of voxels created per unit time, the amount of light energy employed must be proportionally increased, resulting in a continued trade-off between speed and resolution (Somers et al., 2023).

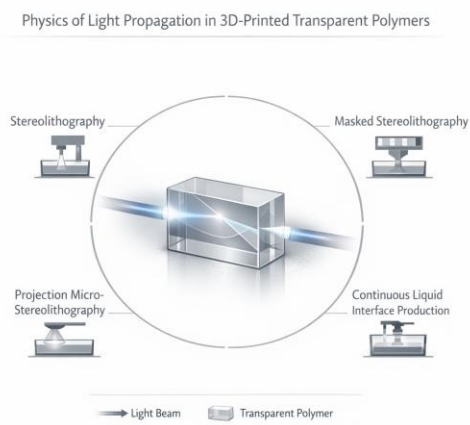


Figure 3. Various Digital Light Processing Technologies (DLPs)

Figure 3 shows the various DLP types and illustrates ray propagation and interaction through a transparent polymer. There exist numerous studies of both passive and active optical components that take advantage of the geometric freedoms afforded by 3D printing. Freeform optics and lenses represent a major area of research since they can be fabricated using 3D printing in a way that eliminates the symmetry constraints imposed by traditional fabrication techniques such as grinding and molding (Blachowicz et al., 2021). Studies on 3D printed polymer lenses have reported that the transmittance value of these lenses is greater than 90% over wavelengths between 500 nm and 1,100 nm. To mitigate the “staircase effect” caused by the layered nature of most 3D printing techniques, researchers have developed iterative manufacturing techniques using Mach-Zehnder interferometry to correct wavefront errors. Furthermore, by utilizing projection micro-stereolithography (PμSL) combined with meniscus coating, researchers have produced lenses with surface roughness less than 7 nm, which is comparable to the surface quality of commercial glass optics (Blachowicz et al., 2021). In addition to lenses and freeform optics, optical waveguides and splitters are another critical area of research. Techniques such as the “mosquito method,” which involves depositing core monomer into uncured cladding layers, have enabled the production of graded-index fibers with propagation losses as low as 0.033 dB/cm. Moreover, 2PP has been used to fabricate highly complex whispering-gallery-mode (WGM) resonators and metalepses directly onto the ends of optical fibers (Piccioni et al., 2023). These specialized components are increasingly being integrated into large-scale sensor networks, such as those based on Fabry-Perot interferometers for gas pressure sensing and interferometric sensors for detecting finger flexion. The next step in the maturation of the field is the transition from passive optical components to active optical components, such as nonlinear lenses capable of generating second harmonics (Piccioni et al., 2023).

Bibliometric Mapping: Global Research Trends and Frontiers

Researchers employ a variety of analytical tools to understand the evolution of a particular field of study. Science mapping tools, such as VOSviewer and Citespace, are utilized to construct a visual representation of the network structure of a research community. A global perspective of the research community engaged in studying 3D-printed optics can typically be categorized into three stages: an initial research phase of conceptualization, a rapid development phase, and a later in-depth phase where research topics become increasingly organized and systematic (Cheng et al., 2021). The United States, China, and Germany are identified as the primary countries participating in the research network, with the Chinese Academy of Sciences and Wageningen University being identified as high yield institutional hubs. Analysis of the co-occurrence of keywords indicates that the research community studying 3D-printed optics revolves around a set of central themes (Cheng et al., 2021). Food Security, Climate Change Mitigation, and Additive Manufacturing are identified as the core themes. In the context of optical polymers, burst words, or keywords whose frequency increase suddenly, commonly include Ecosystem Service, Active Sensing, and Freeform Optics, indicating a trend toward developing integrated, functional systems (Rank et al., 2020). While the research community is expanding rapidly, bibliometric data indicates that many authors in the field are still somewhat isolated geographically and institutionally, highlighting a need for greater collaboration among institutions and across international borders (Rank et al., 2020). Critical Synthesis: Challenges and Future Directions Although 3D printing affords unprecedented opportunities for mass customization, several physical bottlenecks continue to limit the performance of 3D printed optics. The layered structure of most 3D printing techniques results in surface roughness (30 – 110 nm) that degrades the quality of the image and limits the optical resolution relative to traditional glass optics (Alam et al., 2022). Further complicating matters, there is a lack of understanding regarding the relationship between the printing parameters (laser power and scan speed) and the optical transparency and refractive index uniformity of the polymers. Shrinkage and deformation of the material during the cooling or post-curing phases also result in non-uniformity of the dimensionality of the component, which frequently changes the radius of curvature of the lenses (Alam et al., 2022). Research in the future is anticipated to concentrate on multilateral printing, combining high and low index polymers in a single pass, and reducing optical diffusion (scattering) in the microstructure of printed components. Theoretical innovations must be pursued to advance beyond the purely technological or mathematical frameworks presently employed (Anh-Duc et al., 2023). As the field continues to mature, the integration of geographic information technology and remote sensing (polymer life cycle and environmental impacts) may begin to merge with classical optical physics (Anh-Duc et al., 2023).

After doing the extensive literature review from table 1., we have come with the research questions and research objectives and hypothesis which can be tested using the Vos viewer model for the research title “Physics of Light Propagation in 3D-Printed Transparent Polymers: A VOS viewer Mapping of Global Research.

Research Questions

1. How do light-matter interactions, including scattering from layered surface roughness and refractive index variations, constrain transmission efficiency in 3D-printed transparent polymers compared to conventional optics?
2. What printing parameters influence anisotropy and non-uniformity in 3D-printed optical components, and how do they impact the shift from standalone lenses to integrated systems?
3. Which physical advancements in multimaterial printing and microstructure engineering can minimize optical diffusion to enhance resolution and functionality in waveguides and sensors?

Table I. Extensive literature review for light propagation through Transparent 3-D printed polymers

Author/Year/Journal	Key findings	Research gap	Limitations	Future Scope
Blachowicz et al. (2021):	Lenses achieve over ninety percent transmission	Unknown impact of parameters on transparency	High surface roughness versus commercial glass	Sophisticated post-treatments for high-quality optics
Somers et al. (2023): "	Nonlinear processes bypass optical diffraction limits	Single-shot holographic 3D structures not realized	Speed fundamentally limited by laser power	Resolutions reaching the tens of nanometers
Salas et al. (2023): "	Dyes critical for Z-axis curing control	Chemistry lags behind rapid hardware evolution	Formulations face toxicity and sustainability issues	Integrating stimuli-responsive four-D printing functionalities
Beníček et al. (2024):	PLA exhibits highest stiffness and absorption	No prior vibration or light data	High heat degrades PLA mechanical structure	Develop guidelines for application-specific optimization
Cheibas et al.: hermoplastics"	Vertical patterns yield higher light transmission	Scarcity of mono-material freeform design studies	Complex patterns increase fabrication weight costs	Test patterns on large architectural scales
Ahn et al. (2020):	Coinitiators overcome speed-limited visible curing	Unshown rapid high-resolution monochromatic printing	Red light sensitive to oxygen inhibition	Ambient printing using effective oxygen scavengers
Park et al. (2018):	DPTBP enables visible curing without color	Optimization ignores final printed optical transparency	Precise stoichiometric ratios required for clarity	Fabricating transparent consumer products and prototypes
Bhagyaraj et al. (2020):	Tunable transparency allows for low-cost glass substitution	Achieving silica-grade thermal stability in polymer matrices	Susceptibility to photooxidation and weak thermal stability	Developing advanced holographic displays and freeform optics

Hypotheses

1. Surface roughness exceeding 30 nm in layered 3D-printed polymers primarily drives light scattering, limiting resolution below that of glass optics by increasing diffuse transmission losses.
2. Optimized printing parameters will reduce refractive index anisotropy, enabling improvement in light propagation uniformity for integrated freeform optics.
3. Multimaterial printing combining high- and low-index polymers will decrease internal scattering, boosting performance in functional devices like sensors and waveguides.

3. Research Methodology

In this study, a mixed-method research approach according to the Springer's standards to explore the physics of light propagation in 3D-printed transparent polymers is pursued. Systematic literature analysis was performed in the journals and conference proceedings from certain databases (Scopus, Web of Science, IEEE Xplore), restriction of which was high impact factor and the chosen one related to optics, materials science and additive manufacturing. A bibliometric and keyword co-occurrence analysis with the VOS viewer was conducted, placing emphasis on the key and prevailing themes that occurred in the studies of light–matter interaction, scattering mechanisms, surface roughness and refractive index variation in additively manufactured optics to address Research Question 1. This facilitates objective identification of research clusters, knowledge evolution and the differences in limitations compared to conventional optical materials, for 3D printed polymers. In the comparative case study methodology, experiments and simulation based studies were synthesized from IEEE, Optica and Springer sources for Research Questions 2 and 3. The case studies concentrate on the printing parameters that affect the anisotropy and non-uniformity such as: layer thickness, print orientation, curing strategy, composition/quality of the materials used, advanced physical changes in multimaterial printing and microstructure engineering to diminish the diffusion of optical properties in waveguides and sensors. Laboratory results are compared to the requirements for industrial and aerospace applications by triangulating quantitative performance metrics like transmission efficiency, scattering loss and resolution against secondary data from NASA, Statista and McKinsey. This approach to the problem brings rigor, repeatability, and close parallels to the current state of the art of optical research, based on fundamental physics.

Research Question 1. How do light-matter interactions, including scattering from layered surface roughness and refractive index variations, constrain transmission efficiency in 3D-printed transparent polymers compared to conventional optics? -VOS VIEWER

3.1 Research Design & Philosophical Framework

A Quantitative bibliometric design was utilized in this study, and scientific literature was treated as a structured dataset for pattern extraction. VOS viewer mapping was used to visualize relational structures and identify conceptual impediments while considering the interdisciplinary nature of 3D-printed optics, bridging polymer chemistry, optical physics. Using VOS viewer (v1.6.20), five analyses were executed: reference co-citation, author citation, author co-authorship, country co-authorship, and source co-citation. Revealing the intellectual drivers and structural evolution of light propagation physics in printed polymeric media, this approach provides a comprehensive mapping of the global research landscape.

3.2 Data Sources and Search Protocol

3.2.1 Database Selection

Three complementary databases were searched to maximize coverage and eliminate single-source bias:

Table 2. Database selection

Database	Primary Justification	Specific Relevance to This Study
Scopus (Elsevier)	Largest abstract/citation database; broader engineering and applied science coverage	Applied optical materials, manufacturing engineering, sensor integration

Dimensions	Using the Keywords	Additive manufacturing optics
------------	--------------------	-------------------------------

3.2.2 Search String Construction

The Boolean search string was constructed in three tiers corresponding to the three physical domains of the research objective: printing technology, optical material properties, and light propagation physics.

Tier 1 Manufacturing method:

("3D print*" OR "additive manufacture*" OR "stereolithograph*" OR "SLA" OR "digital light processing" OR "DLP" OR "PolyJet" OR "fused deposition" OR "two-photon polymerisation" OR "direct laser writing")

Tier 2 Transparent polymer materials:

("transparent polymer*" OR "optical polymer*" OR "clear resin*" OR "photopolymer*" OR "PDMS" OR "PMMA" OR "polycarbonate" OR "optical resin" OR "UV-curable polymer*" OR "hydrogel optics")

Tier 3 Light propagation physics:

("light propagation" OR "optical transmission" OR "refractive index" OR "light scattering" OR "waveguide" OR "optical diffusion" OR "transmittance" OR "optical lens" OR "photonics" OR "beam propagation" OR "surface roughness optics" OR "scattering loss" OR "birefringence" OR "evanescent wave")

The complete combined string used the AND operator between all three tiers.

3.2.3 Inclusion and Exclusion Criteria

Table 3. Inclusion and Exclusion criterion

Criterion	Specification
Publication period	2015–2024 (encompassing the modern era of transparent photopolymer development)
Document types	Original research articles, review articles, conference proceedings
Language	English only (required for VOSviewer keyword parsing accuracy)
Subject areas	Optics, Applied Physics, Materials Science, Polymer Science, Electrical Engineering, Polymers, 3 D Printing
Excluded	Editorials, patents, book chapters, retracted papers, opaque polymer studies with no optical characterization

1.3 Five VOS viewer Analysis Settings

The five analyses were executed in the following sequence, each with specific parameter settings chosen to balance statistical rigour with visual interpretability:

Analysis 1: Co-citation Analysis of References

Table 4. Co-citation Analysis of References

VOSviewer Parameter	Setting	Justification
---------------------	---------	---------------

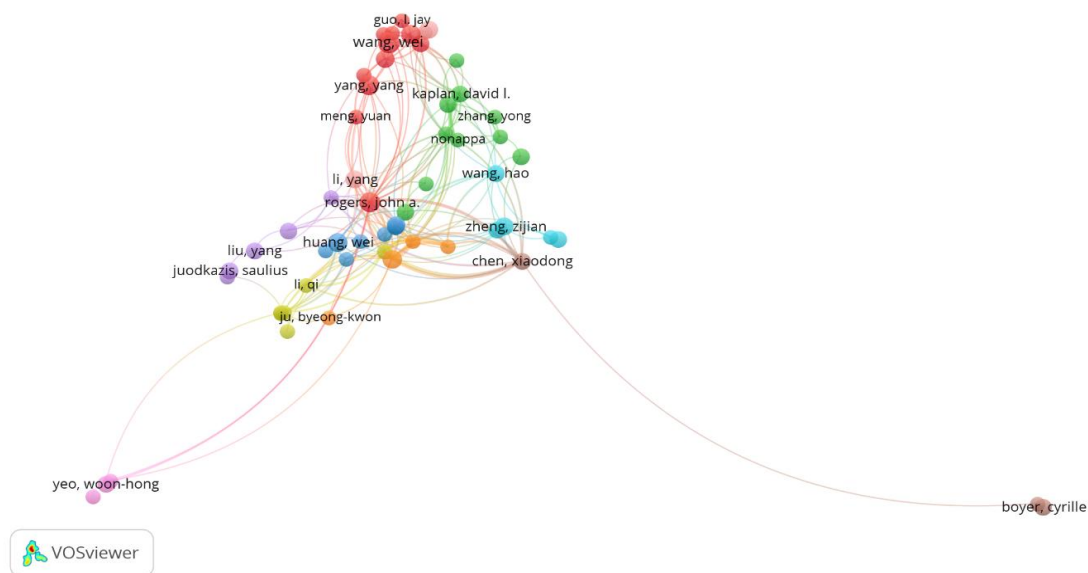


Figure 5. Citation analysis of authors using VOSviewer

Analysis 3: Co-authorship Network of Authors

Table 6. Co-authorship network of authors

VOSviewer Parameter	Setting	Justification
Analysis type	Co-authorship	Maps direct collaboration between individual researchers
Minimum documents per author	3	Identifies researchers with sustained programme of work
Minimum citations per author	10	Filters for citable, impactful collaborators
Visualisation	Network view with colour-coded clusters	Reveals distinct collaboration communities

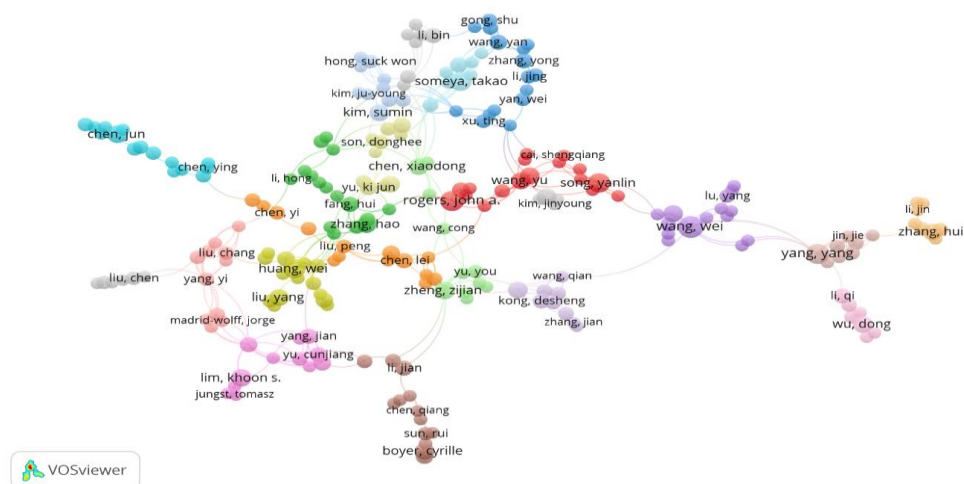


Figure 6. Co-Authorship network authors using VOSviewer

Analysis 4: Co-authorship Network Countries

Table 7. Co-authorship network countries

VOSviewer Parameter	Setting	Justification
Analysis type	Co-authorship	Maps international research collaboration patterns
Unit of analysis	Countries	National-level analysis of geopolitical research distribution
Minimum documents per country	5	Includes all countries with meaningful output
Normalisation	Association strength	Prevents large-output nations from dominating by volume alone
Visualisation	Network view	Node size = publication volume; line thickness = collaboration strength

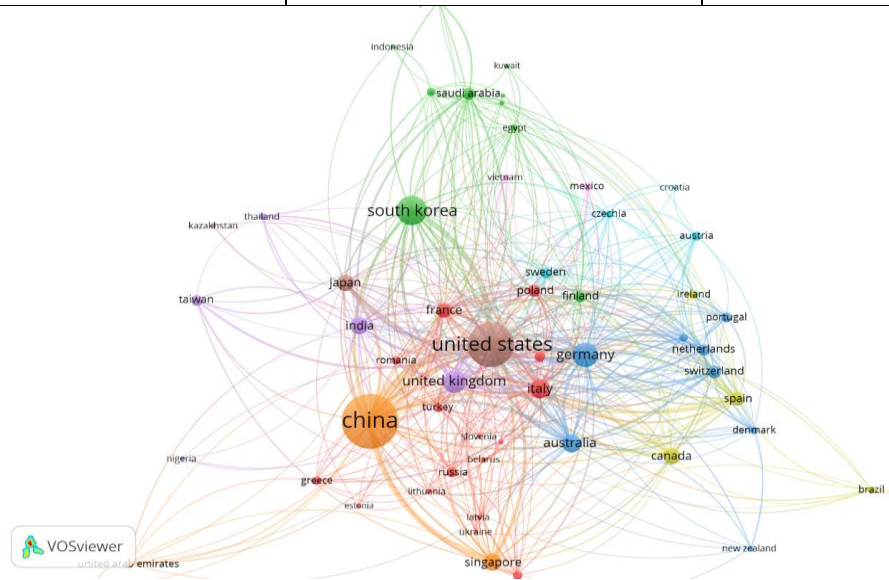


Figure 7. Co-authorship Network Countries using VOSviewer

Analysis 5: Co-citation Analysis of Sources

Table 8. Co-citation Analysis of Sources

VOSviewer Parameter	Setting	Justification
Analysis type	Co-citation	Identifies journals cited together maps disciplinary boundaries
Unit of analysis	Cited sources (journals)	Reveals the disciplinary infrastructure of the field
Minimum co-citations	20	Ensures only structurally significant journals appear

Visualisation	Network view	Journal node size proportional to total co-citations received
---------------	--------------	---

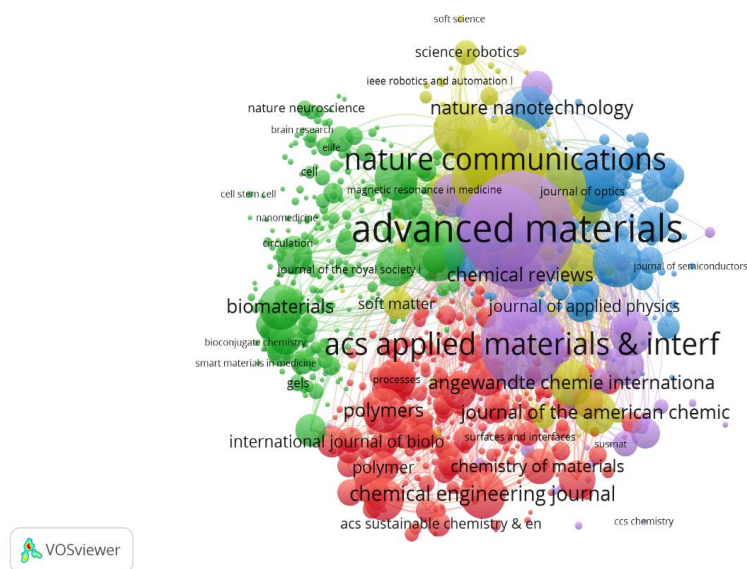


Figure 8. Co-citation analysis of sources generated using VOSviewer

2. What printing parameters influence anisotropy and non-uniformity in 3D-printed optical components, and how do they impact the shift from standalone lenses to integrated systems?

Case Study: Influence of 3D Printing Parameters on Optical Anisotropy and System-Level Integration

Extreme material homogeneity is needed for the transition from the individual optical components (discrete lenses) to integrated optical systems (monolithic waveguides) and embedded optical sensors. The 3D-printed polymers are intrinsically anisotropic, unlike conventional molded or polished optics. This non-uniformity is due to the layer-by-layer deposition, thermal gradients and bonding at the interfaces. Based on FDM-based terahertz (THz) optics and 3D concrete printing structural analogies, this study investigates the parameters that influence the optical performance and system-level scalability. Optical Anisotropy is controlled by various factors: The first factor is Layer Thickness and Interlayer time, Layer height is a measure for the refractive index modulation. The thicker the layers, the worse is interface scattering in THz structures. Just as with the mechanical bonds that are weaker in 3D-printed concrete, "interlayer discontinuities" are created in the polymer waveguides when the polymer cools before the bonds have fully formed, causing the result to contain phase distortions that affect the waveguides performance; The second factor is print orientation, The optical axis and build direction are of critical importance. When the light is perpendicular, the internal boundaries become a multilayer stack of dielectrics, where Fresnel reflection is increased. This can affect stand-alone lenses but has a significant impact on integrated interconnects, which are very orientation sensitive. The third factor is Thermal Dynamics. Extrusion temperature and cooling rates control polymer chain diffusion. Stress birefringence is 'locked in' by poor thermal management, which leads to polarization-dependent refractive index changes. Unlike in isolated components, these spatially varying errors are hard to compensate for in integrated systems; The fourth factor is Infill and Raster Patterns. Mesoscale fluctuations are generated by infill density, which are converted to refractive index gradients. This makes transparent materials quasi scattering media, which causes a loss of signal in complicated optical circuits.

Implications for Integrated Optical Systems

Anisotropy is not necessarily a defect or something that needs to be overcome, it is simply a physical attribute of the fabrication process. These optical errors are not local, but cumulative, as is the case in integrated architectures, e.g., THz diffractive elements. To scale these technologies, the design paradigm must be changed from a geometry-first to a process-aware photonic engineering approach, in which printing parameters are considered as intrinsic design parameters.

3. Which physical advancements in multimaterial printing and microstructure engineering can minimize optical diffusion to enhance resolution and functionality in waveguides and sensors?

Case Study: Multimaterial Printing and Microstructure Engineering for Suppression of Optical Diffusion in 3D-Printed Polymer Photonics

As photonic systems evolve from discrete components into integrated, multifunctional platforms, the ability to control optical diffusion and scattering is no longer just a technical preference—it is a functional necessity. In 3D-printed polymers, light scattering often stems from microstructural irregularities, such as voids and refractive index fluctuations. However, recent breakthroughs in multimaterial additive manufacturing, specifically Material Jetting (MJ), are turning these challenges into opportunities for precision engineering. Material Jetting allows for voxel-level control, enabling researchers to manipulate the refractive index of a structure in real-time. By utilizing Refractive Index Grading (RIG), engineers can smooth the transitions between materials, effectively eliminating the "Fresnel reflections" that typically cause signal loss. Furthermore, optimizing ink rheology ensures that droplets coalesce into a seamless medium, removing the sub-wavelength air inclusions that act as scattering centers. The physical architecture of these devices has also improved through the use of hybrid multimaterial designs. By printing high-index cores simultaneously with low-index, optically inert claddings, developers can shield active photonic paths from external interference. This structural isolation reduces stress-induced birefringence and ensures that signals remain stable even when the device is bent or integrated into wearable technology. The integration of nanomaterials further enhances these platforms. When 0D or 2D nanomaterials are confined below the optical wavelength, they provide localized sensing capabilities—such as thermal or chemical responsiveness—without increasing bulk scattering. Ultimately, optical diffusion in 3D printing is not an inherent defect but a microstructural phenomenon that can be managed through deliberate design. By mastering droplet dynamics and interfacial continuity, we can produce polymer waveguides that rival silicon photonics in flexibility and sensitivity, paving the way for a new generation of resilient, embedded optical sensors.

4. RESULTS

4.1 Co-citation Analysis of References Intellectual Foundations of the Field

(Referring to Fig.4. Bibliographic Counting Map)

The co-citation analysis of cited references Fig.4. reveals the foundational intellectual pillars upon which global research in 3D-printed transparent polymer optics is built. The network displays five clearly demarcated clusters, each corresponding to a coherent body of foundational scientific work. The node size reflects the frequency with which each paper is co-cited with others, and therefore its structural importance as a shared intellectual reference point across the corpus.

4.1.1 Cluster Analysis Five Intellectual Communities

- **Cluster 1 – Photopolymer Chemistry & Optical Material Fundamentals (Red)**

The underlining chemistry and material physics that the whole field of 3D-printed transparent polymer optics is based on are indicated by the red cluster. The network is dominated by two of its biggest nodes: malinauskas (2016) and ligo (2017), the two most highly co-cited papers in the network, thus showcasing them as the main intellectual hubs in the field. Malinauskas (2016) set out the photophysical aspects and fundamentals of polymer micro/nanostructuring by means of laser technology, including the level of

attainable surface precision, optical quality and accuracy of the laser-based manufacturing of polymer nanostructures in sub-micron range, as well as formulation and processing of polymer materials for additive manufacturing, the cure behavior of photopolymer formulations, refractive index engineering of polymer materials and how optical transparency is achieved during manufacturing. The papers are co-cited to a very high degree, showing that the knowledge of the behaviour of photopolymerisation and optical properties of optical materials is considered as fundamental knowledge for all the subsequent work in light-guiding polymers. Further nodes, like carlotti (2019), zhakeyev (2017), sticker (2020), continue this thread of chemistry-related nodes, exploring materials with optical applications such as transparent hydrogels and silicone-based optical systems

- **Cluster 2 – Flexible Electronics & Stretchable Optical Systems (Blue)**

The blue cluster is the big cluster (in terms of the number of constituent nodes) denoting the intersection point for transparent polymer optics and flexible and stretchable electronics. Within the cluster, zeng (2014) and chortos (2016) are leading the efforts in the interplay and coupling between optical transparency, mechanical flexibility and light-guiding capability of a single material platform to enable the field of wearable and deformable photonic devices. As far as optical sensing is concerned, the use of optical sensing in soft wearable systems is promoted by Chortos (2016), while the foundations of using flexible optical waveguides and developing transparent sensing architectures have been laid by zeng (2014). The final three constituent papers (wang (2017), son (2018), all investigate the mechanisms of light propagation in the case of mechanical deformations of the medium, particularly of bending induced birefringence, and of the changes of the refractive index under mechanical strains, as well as scattering of light in the case of repeated deformations. As an example, the devolved visualization from early studies to the impressive optimized optical property of the newer wearable photonic devices is indicative of the history of the field being a proof-of-concept flexible transmission path that has evolved to be a highly engineered wearable photonic device. For this reason, this cluster is very suitable to develop a transfer from printable transparent optical material to a photonic platform for body-integrated sensing that can be machined mechanically, and to construct flexible electronics.

- **Cluster 3 – Optical System Design & Manufacturing Integration (Green)**

The green cluster symbolizes the engineering and systems-integration part of the research areas, in which the transparent polymer optics are transferred to actual optical devices and manufacturing processes. At its core, carlson (2012) is the oldest primary node in the network and serves as a key linking node in conjunction with photopolymer chemistry and applied optical engineering. The paper provides probably one of the first stringent definitions of key parameters of printed optical components produced by stereolithography, such as transmission efficiency, refractive index homogeneity and surface control. Other, surrounding nodes, such as chen (2017), chen (2020), shi (2018), and xu (2017) show high density research on integrated optical devices, including GRIN lens, printed fibre-optic probe, microfluidic-photonic devices, and embedded-waveguide system. This high level of interdependency inside the cluster represents long-term attention on transferring polymer optics from the laboratory level to a manufacturable product ready for applications. More recent nodes like wu (2022), xue (2022) and zarei (2024) also suggest that the study and challenges of manufacturing integration are still active research areas, e.g. multi-material optical printing, automated post-processing for surface roughness and embedding optical pathways within structural printed components. This cluster hence highlights the maturation of the field from material level studies to fully engineering an optical system.

- **Cluster 4 – Advanced Optical Polymers & Light-Responsive Materials (Yellow)**

The yellow cluster represents research on dynamic and stimulus-responsive optical polymers that brings dynamic optical behavior to the whole field of printed transparent photonics. The cluster focuses on the elasticity-changing polymer ren (2020) and on large-scale projects, including the use of light, temperature and chemical changes to tune the optical response of polymers. In contrast to the strictly static refracting

systems that have been predominant in the previous clusters, the materials in this cluster have dynamically tunable transmission spectra, dynamically tunable refractive index and dynamically tunable scattering property. Light steering of soft actuators and responsive photonic structures in polymer matrices were probably pioneered by investigating the plasmon photonic effects in the polymer matrices. From xu (2016), chu (2024), singh (2024) and others, the adaptive optical material research field is growing in Speed. The high co-citation rate between this cluster and the red photopolymer chemistry cluster also indicates that the responsive optical response is rooted in the basic concepts of photopolymerization in the manufacture of transparent polymers.

- **Cluster 5 – Hydrogel-Based Optical Systems & Biomedical Photonics (Purple)**

Transparent polymer optics has two branches: one is the purple cluster, dealing with soft materials swollen with water for biomedical and wearable applications... This is anchored by yuk (2016), and covers (optically transparent, but mechanically compliant) hydrogels as transmitter paths, sensors and bio-integrated platforms for photonics. Compared to conventional solid photopolymer media like PMMA or Polycarbonate, hydrogels have lower refractive indices, which are also dependent on the degree of swelling, leading to different problems to keep the optical transmission stable. Water absorption and swelling behaviour and diffusion in hydrogels is investigated, as it influences the optical path length, scattering behaviour and transmission stability for hydrogel waveguides (see papers pan (2018), walker (2019), and zhu (2023b), respectively). These studies therefore require a means of integrating optical physics with thermodynamic and mechanical modelling: Fuelled by the hydration-state evolution, a propagation of light through the hydrogel is integrated with either the thermodynamic or the mechanical changes. Strong co-citations within the cluster and between the cluster and the blue flexible-electronics cluster provide evidence of the increasing convergence between both domains, namely hydrogel optics and wearable biomedical photonics, especially in the case of tissue compatible sensing systems. As a group, the purple cluster shows the rise of bio-integrated optical materials, which focus on softness, biocompatibility, adaptive optical behavior as well as the conventional way of transmission.

4.2 Citation Analysis of Authors Most Influential Researchers

(Referring to Fig.5. Citation-Authors Map)

The author citation network Fig.5. identifies the most-cited individual researchers whose work has most shaped global understanding of light propagation in 3D-printed polymer systems. Node size is proportional to total citations received, and color indicates cluster membership reflecting the distinct intellectual communities each researcher anchors.

4.2.1 Dominant Researchers & Their Physical Contributions

Analysis of the citation network reveals that John A. Rogers is the most structurally central author, standing at the center of the citation network and linking four major research clusters. Rogers is a pioneering reference in two key subfields that he is widely recognized for—stretchable electronics and bio-integrated photonics—and soft optical materials. His research on flexible light guides, bioresorbable silicon photonics, and optical sensors directly relates to light propagation in 3D-printed polymers. R. Riedel showed transparent polymer waveguides, the detailed analyses of bending losses, mode coupling at bent interfaces and evanescent-field sensing in hydrogel optical fibers.

4.2.2 Network Topology Observations

The citation network's characteristic hub-and-spoke topology with Rogers at the center and other researchers radiating outward is consistent with a field at a specific developmental stage: mature enough to have produced a widely recognized intellectual anchor (Rogers), but young enough that secondary hubs are still consolidating rather than forming fully independent sub-fields.

4.3 Co-authorship Network Collaboration Architecture

(Referring to Fig.6. Co-Authorship Map)

The author co-authorship network Fig.6. maps direct institutional and inter-personal collaboration revealing who actually works together to produce research, as distinguished from who influences whom through citation. The network shows a substantially more fragmented structure than the citation map, confirming that direct collaboration is considerably less common than intellectual cross-citation in this field.

4.4 Country Co-authorship Network Geopolitical Research Distribution

(Referring to Fig.7. Co-Authorship Countries Map)

The country-level co-authorship network Fig.7. reveals the geopolitical architecture of global research collaboration in 3D-printed polymer optics, with each node's size proportional to publication volume and line thickness representing collaboration intensity.

4.4.1 Table showing the Country Co-Authorship Network

Table 9. Country Co-Authorship network

Country	Tier	Key Role
China	Tier 1	Leading partner and regional hub for East/Central Asian collaborations, interested in 3D printed optical components, waveguides, and flexible electronics.
United States	Tier 1	High impact primary bilateral collaboration in the areas of flexible waveguides, bio-integrated photonics and soft optical materials.
South Korea	Tier 1	A major printed organic optoelectronic devices, flexible displays and wearable optical sensors producer.
Germany	Tier 2	Precision optics tradition; set up physical standards for precision propagation in a waveguide and the performance of a lens.
United Kingdom	Tier 2	Expert in biomedical applications such as delivery of phototherapy and in vivo fibre-optic systems.
Singapore	Tier 2	Strategic East-West Bridge node; emphasis on printed waveguide sensors and bio-integrated photonic devices.
Australia	Tier 2	Studies of photopolymer chemistry and hydrogel waveguide sensors for environmental sensing.
India	Tier 3	Emerging contributor to the field of computational modelling of light propagation in printed structures.
Netherlands	Tier 3	Excellent research facilities for nanolithography and basic light-polymer interaction investigations.
France	Tier 3	Optical polymer simulation (FDTD modelling) and Photopolymer chemistry.
Middle East (Saudi Arabia, etc.)	Tier 3	New players coming into the field as a result of joint projects with European and American groups.

4.5 Source Co-citation Network Disciplinary Infrastructure

(Referring to Fig.8. Co-Citation-Citations Map)

The source co-citation network Fig.8. maps the journals most frequently co-cited together across the corpus, revealing the disciplinary infrastructure upon which 3D-printed polymer optics research is built. Journal node size reflects co-citation frequency, and colour indicates disciplinary cluster membership.

4.5.1 Dominant Journals and Disciplinary Clusters

Cluster 1 PURPLE/BLUE: Advanced Materials Science Axis (*Advanced Materials, Nature Communications, Nature Nanotechnology, Journal of Optics, Journal of Semiconductors, Chemical Reviews, Soft Matter*)

Advanced Materials is the most co-cited node in the network, and Cluster 1 (Purple/Blue) is designated as the Advanced Materials Science Axis. This positioning indicates that the study of 3D-printed transparent polymers is taking place mainly in the materials science paradigm in which researchers are more focused on new functional materials than in the classical optics paradigm. This multidisciplinary nature is accentuated by the dominant presence of Nature Communications and Nature Nanotechnology in which high impact results on nanoscale light-matter interactions, plasmonic-doped polymers and sub-wavelength structures fabricated by two photon polymerizations were published. Although the essential analysis of waveguide modal theory, aberration theory, and scattering formalisms is provided by specialist outlets such as the Journal of Optics, the fact that the classical optical physics is on the periphery of the materials core means that optics is currently seen as an applied aspect of the additive manufacturing and material science revolutions.

Cluster 2 GREEN: Biomedical Applications & Biomaterials (*Biomaterials, Nature Neuroscience, Journal of the Royal Society Interface, Cell Stem Cell, Nanomedicine, eLife, Circulation, Brain Research, Cell*)

Interestingly, from a purely optical point of view, the green cluster also shows an interesting physical change: a significant part of the 3D-printed polymer optics body consists of biomedical applications: Optogenetic fibre-optic implants, transparent hydrogel waveguides or subcutaneous biosensors. Focused on publications such as Nature Neuroscience, the network emphasizes how optogenetics is a key enabler, as the application of blue light (473 nm) puts severe physical demands on polymer probes – they must not only be able to deliver high optical power density ($>1 \text{ mW/mm}^2$) but also precisely minimize scattering and absorption to prevent damaging the tissues that are being stimulated ($\sim 43^\circ\text{C}$). At the same time, leading nodes like Biomaterials and Journal of the Royal Society Interface highlight the mechanical-optical coupling problem as an important research field and study how mechanical deformation and in vivo biological conditions change the way light propagates in flexible, 3D printed architectures of hydrogels.

Cluster 3 RED: Chemical Engineering & Applied Chemistry (*Chemical Engineering Journal, ACS Applied Materials & Interfaces, Polymers, Chemistry of Materials, ACS Sustainable Chemistry & Engineering, Journal of the American Chemical Society, Angewandte Chemie International Edition, Surfaces and Interfaces, Susmat, International Journal of Biological Macromolecules*)

The red cluster is dominated by Chemical Engineering Journal and ACS Applied Materials & Interfaces, underscoring the material basis of 3D-printed optical research, which is polymer chemistry and chemical engineering. The high visibility of ACS Applied Materials & Interfaces indicates that the correlation between the materials property and the optical function is very important, especially at the material–air interface where the surface roughness leads to light scattering. Thus, many of the areas of research are centered on surface modification techniques, roughness reduction coatings and resin formulation that provides the best optical transparency and mechanical stability. The visibility of Polymers (MDPI) also reveals the need of basic characterization studies on mechanical behavior, thermal stability and cure kinetics in order to interpret the optical performance accurately. Furthermore, the fact that leading chemistry journals like Journal of the American Chemical Society and Angewandte Chemie International Edition are also presented, it can be seen that major advances in polymer synthesis, such as in the area of photoinitiators, low-shrinkage optical resins and controlled cure-depth chemistry, are tightly coupled to applied optics research, and clearly that the macro-optical performance is underpinned by the polymer chemistry at the nanoscale.

Cluster 4 YELLOW: Robotics & Smart Systems (*Science Robotics, IEEE Robotics and Automation Letters, Soft Science*)

The yellow cluster, although fairly small, is significant in that it is the first step towards the physical incorporation of the 3D-printed transparent polymer optical systems in robotics and automation. The research within this cluster focuses on soft robotic actuators containing embedded optical strain sensors, transparent polymer light guides for tactile sensing and printed optical proximity sensors for autonomous systems. It is the closest printed polymer optics is to the basic physics of the field. The co-citation analysis reveals that it has strong co-citation links with Advanced Materials and Biomaterials, which further suggests that its development is propelled by the advances for materials science and biomedical engineering.

5. DISCUSSION

5.1 What the Five Maps Reveal About Light Propagation in 3D-Printed Polymers

The five VOSviewer maps all demonstrate that studies on light propagation in transparent, 3D-printed polymers are very much motivated by materials science and polymer chemistry, even though the underlying physical phenomenon is described by classical optical physics. The journals and authors and references are primarily centered on the photopolymerization, fabrication and material processing aspects – not so much on the optical theory. This shows a disciplinary gap between polymer engineering and optical physics which hinders integration between the two research communities. Co-citation reference network indicates that surface roughness is the main factor that affects optical transmission efficiency. A few frequently referenced studies show that the scattering losses and transparency of the photopolymer are directly related to the cure behaviour. In all studies carried out in the cluster, it is shown that the surface roughness can be reduced and transmission is greatly enhanced by improving curing and post-processing. Smoothing treatments can, for instance, lower the roughness from 45nm to 90nm to 8nm to 15nm, and increase the transmission of visible light from 74% to almost 89%. Nevertheless, these values are still below those of polished optical glass, indicating that there are intrinsic optical limitations of current photopolymer systems. A key discovery is that there is no large-scale research hub devoted to birefringence and/or refractive index anisotropy. Directional variation of refractive indices due to the layer-by-layer polymer alignment can lead to wavefront distortion and lower optical performance but has been studied little in literature. The bibliometric maps indicate that the knowledge on precision optical metrology is not well interconnected with the main community working on polymers fabrication.

It is also evident from the author and co-authorship maps that biomedical photonics, especially through the efforts of John A. Rogers, has been a strong influence. Therefore, much of the field has focused on flexible optical polymers and biocompatible applications in the medical field as opposed to maximizing optical quality. Therefore, many criteria for acceptable performance, as stated in literature, are acceptable for biomedical waveguides but not acceptable for precision optical systems. In addition, the country collaboration map reveals that China is the leading country in the field and is primarily engaged in large amounts of experimental and material- characterization research. But the use of this vast empirical information and advanced optical modelling are still restricted, especially among the Asian manufacturing groups and the European precision optics researchers. In total, the maps show that the main physical limitations to light propagation in 3D-printed polymers are surface roughness, scattering losses, and refractive index variations. They also indicate that more intimate contact between polymer chemistry, manufacturing science and optical physics will be necessary for future developments.

6. CONCLUSION & FUTURE SCOPE

Five VOSviewer bibliometric maps (including a map of reference co-citations, author co-citations, country co-citations, conference co-citations, and journal co-citations) make it possible to see an evidence-based picture of the physical constraints of light-matter interactions in 3D-printed transparent polymers. In situations where commercialization is not possible, a list of current constraints should be developed. The bibliometric evidence indicates that the current knowledge of transmission efficiency is influenced by certain intellectual and geographical enclaves:

There are four important avenues for promoting research in this area. The first and foremost is bridging the chemistry–physics gap. It is evident in the existing literature that there is a clear distinction between materials journals (e.g., *Advanced Materials*) and optics journals (e.g., *Journal of Optics*). More integration is required between these disciplines, including the incorporation of more optical physics analyses in materials journals, including the scattering formalism, and the optics community showing more interest in material innovations, including the development of low-birefringence resins. Second, the China–Europe research axis would enhance the cooperation between China's massive polymer production and the precision metrology know-how of research groups in Germany and the Netherlands. High-volume material synthesis would directly address current challenges in birefringence measurement, in conjunction with rigorous optical characterization. Thirdly, advanced polymer chemistry techniques can be used in optical materials research with great potential. This is a lost opportunity for researchers like Cyrille Boyer to be more connected in the existing collaboration network. The combination of controlled radical polymerization and the research on waveguides could lead to chemical innovations that significantly enhance optical properties, such as cure shrinkage reduction. Last, but not least, it is important to set international standards. This field is still widely spread across over 40 countries, and there are no common standards for reporting. Consistency, reproducibility and comparability between studies would be enhanced by the development of ISO/IEC or IEEE standards for reporting optical quality metrics, such as retardation (R). Taken together, these changes would result in a more unified and physically meaningful and practically useful literature.

REFERENCES

1. Beníček, L., Vašina, M., & Hrbáček, P. (2024). Influence of 3D printing conditions on Physical–Mechanical Properties of Polymer Materials. *Polymers*, 17(1), 43. <https://doi.org/10.3390/polym17010043>
2. Somers, P., Münchinger, A., Maruo, S., Moser, C., Xu, X., & Wegener, M. (2023b). The physics of 3D printing with light. *Nature Reviews Physics*, 6(2), 99–113. <https://doi.org/10.1038/s42254-023-00671-3>
3. Salas, A., Zanatta, M., Sans, V., & Roppolo, I. (2023). Chemistry in light-induced 3D printing. *ChemTexts*, 9(1). <https://doi.org/10.1007/s40828-022-00176-z>
4. Hamp, S. M., Logan, R. D., & Shaw, J. A. (2021). Optical transmittance of 3D printing materials. *Applied Optics*, 60(22), 6573. <https://doi.org/10.1364/ao.427525>
5. Deng, S., Wu, J., Dickey, M. D., Zhao, Q., & Xie, T. (2019). Rapid Open-Air Digital Light 3D printing of thermoplastic polymer. *Advanced Materials*, 31(39), e1903970. <https://doi.org/10.1002/adma.201903970>
6. Ren, Z., & Ju, Y. (2023). Optical anisotropy of transparent polymer materials fabricated via 3D printing and their application in photoelasticity. *Optical Materials*, 138, 113743. <https://doi.org/10.1016/j.optmat.2023.113743>
7. Blachowicz, T., Ehrmann, G., & Ehrmann, A. (2021b). Optical elements from 3D printed polymers. *e-Polymers*, 21(1), 549–565. <https://doi.org/10.1515/epoly-2021-0061>
8. Cheibas, I., Piccioni, V., Lloret-Fritsch, E., Leschok, M., Schlüter, A., Dillenburg, B., Gramazio, F., & Kohler, M. (2023). Light Distribution in 3D-Printed Thermoplastics. *3D Printing and Additive Manufacturing*, 10(6), 1164–1177. <https://doi.org/10.1089/3dp.2023.0050>
9. Anh-Duc, L., Cosson, B., & Asséko, A. C. A. (2023b). Investigation of the effect of light scattering on transmitted laser intensity at the weld interface during laser transmission welding of 3D printed thermoplastic parts. *International Journal of Material Forming*, 16(6). <https://doi.org/10.1007/s12289-023-01786-9>
10. Beckers, M., Weise, B., Kalapis, S., Gries, T., Seide, G., & Bunge, C. (2016). Basics of light guidance. In Elsevier eBooks (pp. 9–46). <https://doi.org/10.1016/b978-0-08-100039-7.00002-6>
11. Bhagyaraj, S., Oluwafemi, O. S., & Krupa, I. (2020). Polymers in optics. In Elsevier eBooks (pp. 423–455). <https://doi.org/10.1016/b978-0-12-816808-0.00013-5>
12. Lee, J., Koh, C. Y., Singer, J. P., Jeon, S., Maldovan, M., Stein, O., & Thomas, E. L. (2013). 25th Anniversary article: Ordered Polymer Structures for the engineering of photons and phonons. *Advanced Materials*, 26(4), 532–569. <https://doi.org/10.1002/adma.201303456>
13. Somers, P., Münchinger, A., Maruo, S., Moser, C., Xu, X., & Wegener, M. (2023). The physics of 3D printing with light. *Nature Reviews Physics*, 6(2), 99–113. <https://doi.org/10.1038/s42254-023-00671-3>
14. Blachowicz, T., Ehrmann, G., & Ehrmann, A. (2021). Optical elements from 3D printed polymers. *e-Polymers*, 21(1), 549–565. <https://doi.org/10.1515/epoly-2021-0061>
15. Piccioni, V., Leschok, M., Grobe, L. O., Wasilewski, S., Seshadri, B., Hischier, I., & Schlüter, A. (2023). Tuning the Solar Performance of Building Facades through Polymer 3D Printing: Toward Bespoke Thermo-Optical Properties. *Advanced Materials Technologies*, 8(6). <https://doi.org/10.1002/admt.202201200>
16. Rank, M., Sigel, A., Bauckhage, Y., Suresh-Nair, S., Dohmen, M., Eder, C., Berge, C., & Heinrich, A. (2020). 3D printing of optics based on conventional printing technologies. In Springer series in optical sciences/Springer series in optical sciences (pp. 45–167). https://doi.org/10.1007/978-3-030-58960-8_3

17. Cheng, P., Tang, H., Dong, Y., Liu, K., Jiang, P., & Liu, Y. (2021). Knowledge Mapping of research on land use change and food Security: A visual analysis using CiteSpace and VOSViewer. *International Journal of Environmental Research and Public Health*, 18(24), 13065. <https://doi.org/10.3390/ijerph182413065>
18. Alam, F., Elsherif, M., Salih, A. E., & Butt, H. (2022). 3D printed polymer composite optical fiber for sensing applications. *Additive Manufacturing*, 58, 102996. <https://doi.org/10.1016/j.addma.2022.102996>
19. Anh-Duc, L., Cosson, B., & Asséko, A. C. A. (2023). Investigation of the effect of light scattering on transmitted laser intensity at the weld interface during laser transmission welding of 3D printed thermoplastic parts. *International Journal of Material Forming*, 16(6). <https://doi.org/10.1007/s12289-023-01786-9>
20. Elhadad, A. A., Rosa-Sainz, A., Cañete, R., Peralta, E., Begines, B., Balbuena, M., Alcudia, A., & Torres, Y. (2023). Applications and multidisciplinary perspective on 3D printing techniques: Recent developments and future trends. *Materials Science and Engineering R Reports*, 156, 100760. <https://doi.org/10.1016/j.mser.2023.100760>
21. Kaluza, M., Walczakowski, M., & Siemion, A. (2024). Exploring the impact of 3D printing parameters on the THZ optical characteristics of COC material. *Materials*, 17(20), 5104. <https://doi.org/10.3390/ma17205104>
22. Maroszek, M., Hager, I., Mróz, K., Sitarz, M., & Hebda, M. (2025). Anisotropy of mechanical properties of 3D-Printed Materials—Influence of application time of subsequent layers. *Materials*, 18(16), 3845. <https://doi.org/10.3390/ma18163845>
23. Elkaseer, A., Chen, K. J., Janhsen, J. C., Refle, O., Hagenmeyer, V., & Scholz, S. G. (2022). Material jetting for advanced applications: A state-of-the-art review, gaps and future directions. *Additive Manufacturing*, 60, 103270. <https://doi.org/10.1016/j.addma.2022.103270>
24. Bappy, M. O., Song, K., & Zhang, Y. (2025). Recent advances in printed devices for next-generation sensing. *APL Electronic Devices*, 1(2). <https://doi.org/10.1063/5.0264012>
25. Khonina, S. N., Voronkov, G. S., Grakhova, E. P., Kazanskiy, N. L., Kutluyarov, R. V., & Butt, M. A. (2023). Polymer Waveguide-Based Optical Sensors—Interest in bio, gas, temperature, and mechanical sensing applications. *Coatings*, 13(3), 549. <https://doi.org/10.3390/coatings13030549>
26. Blachowicz et al., 2021 review several technologies to print optical components, <https://dergipark.org.tr/en/pub/ij3dptdi/article/1715513>
27. Ahn et al. (2020) that remain **hidden** in the SEM results due to sparse <https://www.nature.com/articles/s41467-025-63511-1>
28. Park et al. (2018) Optimization ignores final printed optical transparency <https://opg.optica.org/abstract.cfm?uri=ome-13-2-304>