Next Generation Optical Materials and Components for High-Power, High-Energy Lasers

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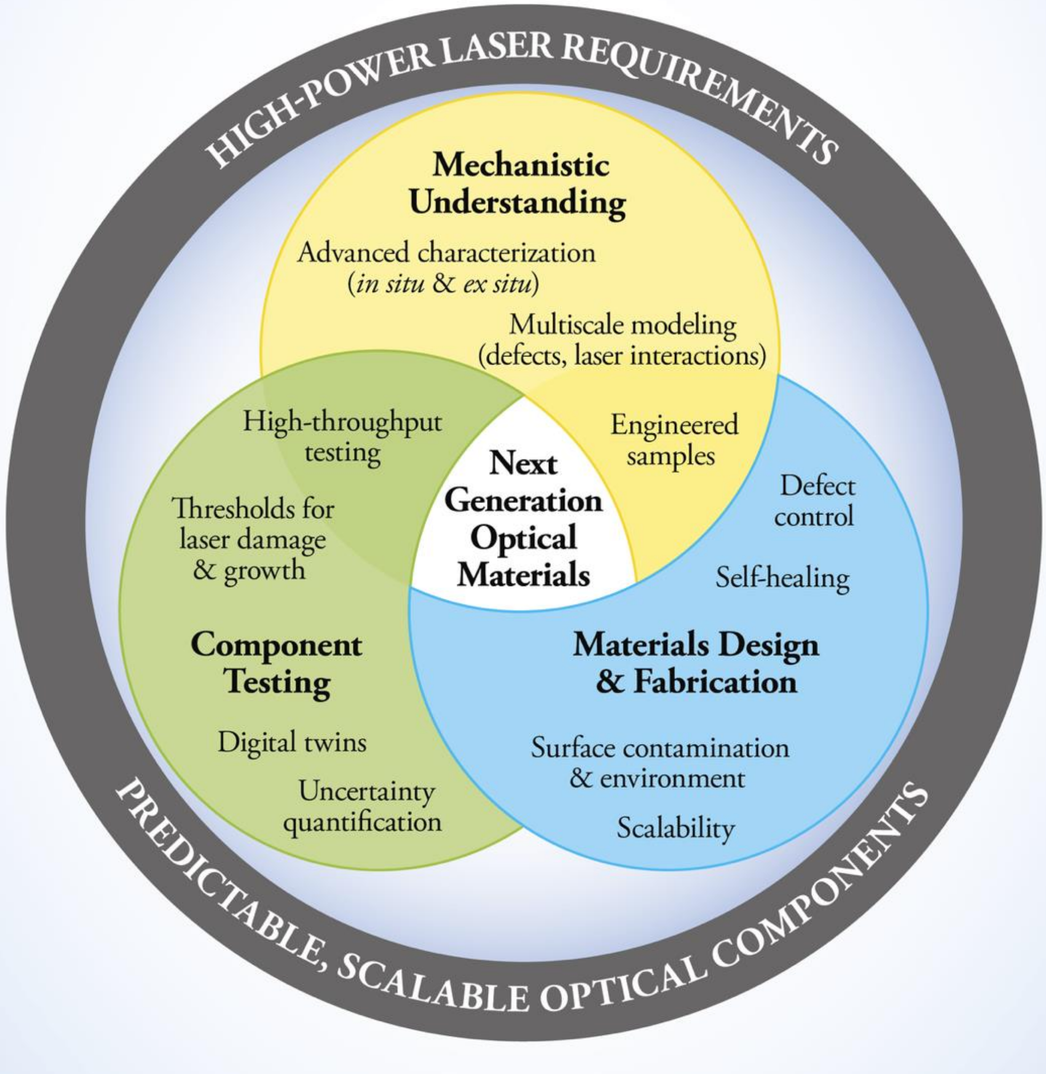

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Executive Summary

Motivated by the demanding requirements of future national assets, such as the proposed NSF OPAL facility and urgent Department of War needs, a targeted workshop was convened to address a critical bottleneck in laser technology. This brief report outlines the resulting strategy, which focuses on overcoming the performance and reliability limitations of passive optical components—such as mirrors, coatings, and gratings. This initiative brought together leaders from industry, academia, and government agencies, including the U.S. National Science Foundation (NSF), the Air Force Office of Scientific Research (AFOSR), and Department of War and Department of Energy laboratories, with the goal of bridging the long-standing gap between the laser and materials science communities.

The key technical conclusion from the workshop is clear: the primary obstacle to advancing high-power lasers is the performance and reliability of currently available optical materials. Limitations arise from a combination of factors, including defect-driven damage initiation, variability in material quality, environmental sensitivity of optical surfaces, and the complexity of fabricating large, high-performance optical components. Current manufacturing of critical components often relies on inconsistent, "artisan-like" expertise, leading to variability in material quality and optical performance. These challenges hinder the translation of laboratory advances into reliable optical components and highlight the need for improved control of materials, microstructure, and fabrication processes. At the same time, new materials and optical architectures that reduce sensitivity to fabrication constraints or mitigate the need for extremely large apertures represent important opportunities for future systems.

This report calls for a transition from largely empirical optimization toward a predictive, science-based framework for materials design, fabrication, and performance assessment. The workshop identified three mutually reinforcing priorities for achieving this transition:

Achieve a mechanistic understanding of laser-induced failure. Progress requires moving beyond observation of damage thresholds toward the design of next-generation optical materials based on a deeper understanding of damage initiation, incubation, and growth. This calls for coordinated advances in materials characterization, time-resolved diagnostics, and multiscale modeling capable of linking electronic excitation, defect dynamics, and structural evolution.

Establish an integrated materials design and fabrication loop. Mechanistic understanding should be translated into predictive materials design and manufacturing strategies through an iterative feedback cycle in which predictive 'digital twins'—physics-informed simulations that mirror the entire lifecycle of a physical component from fabrication to failure—inform materials selection, guide fabrication processes, and accelerate experimental validation. This approach enables deliberate engineering of optical materials and components resilient to known failure mechanisms.

Leverage data-driven methods to accelerate discovery. Modern computational tools, including machine learning and artificial intelligence, enable exploration of the complex parameter spaces associated with materials composition, fabrication processes, and component design. Combined with experimental data and physics-based modeling, these tools can effectively manage complexity, quantify uncertainty, and accelerate the discovery cycle from hypothesis to validation.

Beyond strengthening existing research directions, the workshop emphasized the need for deeper integration across traditionally separate laser, materials science, fabrication and computational modeling communities, and for expanded shared infrastructure for advanced characterization and testing of optical materials and components. Implementing this integrated roadmap will enable the community to address the materials science bottleneck limiting the deployment of the next generation of high-power laser systems.

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1. Introduction

This brief report summarizes findings on next-generation optical materials for high-power laser components. The workshop and this report focus on materials for optical components, in particular diffraction gratings, which are essential for applications like pulse compression and spectral beam combining. The development of laser gain media (host materials), while critical to laser systems, was intentionally outside the scope of the workshop. The report details the primary classes of materials used for gratings, mirrors, and coatings and outlines the key challenges and future directions for their development.

The expansion of the operational envelope of high-power, high-energy laser systems, which are critical for both scientific discovery and national security, is fundamentally constrained by performance limitation of the constituent optical materials and components. These limitations are typically manifested as functional degradation, leading to loss of laser output, and/or catastrophic damage. This technological barrier directly impacts the size, weight, and power (SWaP) of next-generation platforms, hindering the development and feasibility of critical systems such as directed energy weapons, laser systems for basic science, and an array of potential future applications including inertial fusion energy. The accelerating demand for increase in peak and average laser power, coupled with the variability of operational environments and regimes, creates an urgent need to achieve performance breakthroughs through a deeper understanding of underlying failure mechanisms and the development of effective mitigation strategies.

To accelerate progress, a comprehensive, multidisciplinary strategy is required to optimize the fabrication methods of optical materials and develop degradation-resistant optical components. Importantly, the optical component designs must be tailored to be compatible with the use environment. Although a plurality of optical components is incorporated in modern laser systems, it is recognized that the “weak link” in terms of performance are the transport optics, including mirrors, gratings and other components utilizing materials deposited via physical vapor deposition methods. The issue stems from the difference between the coating materials produced by currently adopted technologies and their bulk counterparts that often contain various electronic and structural defects that degrade performance. Challenges in optical coating fabrication extend beyond material quality to include scaling to larger apertures, control of internal stresses, meeting optical specifications, and ensuring long-term stability. This multi-parameter space, where optimizing one parameter may compromise another, leads to trade-offs that are difficult to manage with existing tools and approaches. Advancing fabrication techniques therefore requires a multidisciplinary multipronged effort spanning fundamental material science, advanced material characterization, and predictive modeling.

To launch this integrated effort and bridge the long-standing gap between the laser and material science communities, a targeted workshop was convened. This initiative was directly motivated by the demanding design requirements of future national assets, including the proposed NSF OPAL laser facility, and the urgent needs of the Department of War. The workshop was attended by a significant number of industry participants, as well as scientists and engineers from institutions of higher education in the US and abroad, and researchers and program officers from the Air Force Office of Scientific Research (AFOSR), U.S. National Science Foundation (NSF), Department of War laboratories (Air Force Research Laboratory, U.S. Naval Research Laboratory, U.S. Army Research Laboratory), and Department of Energy-supported laboratories (Lawrence Livermore National Laboratory, Laboratory for Laser Energetics).

A key technical conclusion of the workshop confirms that expanding the output power of high-power lasers is limited not by laser physics alone, but by the reliability and lifetime of the currently available optical materials and coatings. A critical pillar of the strategy that emerged from the workshop discussions is the integration of manufacturing methods with next generation on-line diagnostics and advanced computational modeling. Such integration would enable development of a mechanistic understanding of defect behavior and address the inherent variability and stochastic nature of optical material failure. Small, often undetectable manufacturing defects, contamination, and environmentally driven variability can lead to stochastic damage initiation, gradual aging, and eventual catastrophic failures. Developing a strategic approach centered on a "materials development loop," an integrated cycle connecting fundamental studies, including multiscale modeling of relevant material structures, with materials synthesis, component fabrication, and rigorous characterization and testing, is of fundamental importance. A critical component of this loop is developing capabilities for detailed characterization of the material defect structures responsible for performance degradation, tracking their incubation and evolution to enable accurate lifetime prediction, and feeding that data back to inform the next cycle of fundamental research and material design. Of particular interest is understanding of the electronic and structural defects at interfaces and in coating materials, including compositionally complex crystalline or amorphous phases, as well as surface photochemical processes driven by laser irradiation and environmental exposure.

Accurate assessment of the optical component performance in operational environments necessitates the development of predictive, decision-ready models using uncertainty quantification and scientific machine learning tools. These models will be used to (i) improve manufacturing and metrology, (ii) accelerate component qualification, and (iii) enable reliability-aware laser operation. Emerging agentic artificial intelligence (AI) systems can further accelerate this discovery loop by orchestrating the integration of literature, experimental data, and multi-physics simulations to build and continuously refine predictive digital twins. The workshop participants highlighted the limited engagement of the scientific community that produces widely shared knowledge in optical materials due to lack of resources for basic research along with severe shortage of shared instrumentation for fabrication of complex optical components such as pulse compression and spectral beam combining gratings.

This report summarizes the findings and recommendations that emerged from this collaborative workshop. It begins by defining the state-of-the-art and future requirements for high-power laser components and materials, from reflective and transmissive optics to next-generation concepts like metamaterials, reactive optics, and self-healing systems. Emphasis is placed on efforts to understand and mitigate the underlying mechanisms of laser damage, advocating for an integrated approach that combines advanced fabrication and characterization tools with multiscale modeling, towards optimizing current-generation optical materials and developing next-generation materials with substantially improved performance. Building on this mechanistic foundation, a strategy for the predictive design of new materials is outlined, leveraging data-driven methods and machine learning to accelerate the discovery of novel compositions. Finally, the report highlights unique fabrication challenges associated with gratings and other metasurfaces, where additional processing steps can further exacerbate material performance limitations. Collectively, this report presents an overview of a comprehensive roadmap for future research and development and identifies critical gaps that must be addressed to achieve meaningful advances in SWaP performance and reproducibility.

2. Components and Materials for High-Power, High-Energy Laser Systems

High-power and high-energy laser systems rely on a diverse set of optical components whose performance and reliability ultimately determine system capability and lifetime. These include reflective and transmissive optics, dielectric mirrors and coatings, and metallic or metal-dielectric hybrid elements. Advances in metamaterials and active optics may enable new approaches to wavefront and spectral control, while emerging concepts such as plasma-, gas-, or liquid-based optics with self-healing properties could help address the challenges associated with extremely high energies, peak intensities, and harsh operating environments. Together, these technologies expand the optical component toolbox needed to meet increasingly stringent requirements on material durability and performance and to enable more compact and efficient laser systems.

At the system level, performance is often limited by the weakest link in the chain of transport optics. In practice, particular attention must be devoted to components based on multilayer dielectric coatings, including mirrors, antireflective coatings, and diffraction gratings. These elements frequently operate near their damage thresholds and therefore represent a primary bottleneck in scaling laser performance. The maximum sustainable laser power (instantaneous or average) is ultimately determined by fundamental material properties such as optical bandgap, linear and nonlinear absorption, the formation of stable color centers under irradiation, and surface photochemistry under realistic operating conditions.

At the component level, further scaling of laser power and energy is constrained by electromagnetic field localization, thermal loading, and mechanical stress. Local field enhancement can produce hot spots that promote damage initiation. These hot spots may arise from component design features (*e.g.*, multilayer dielectric coatings or grating pillars) and are typically mitigated through design strategies aimed at maximizing the laser-induced damage threshold (LIDT). However, localized energy concentration can also originate from imperfections such as coating nodules, deviations in grating geometry, or contamination introduced during handling or operation.

In large-aperture, high-power laser systems, damage initiation at isolated sites is often unavoidable. The critical requirement therefore is that these damage sites remain stable and do not expand under subsequent laser irradiation. Laser-induced damage growth can lead to runaway processes that ultimately cause catastrophic failure of the optical component and potentially downstream optics. In this regime, the laser-induced damage growth threshold becomes a more relevant metric than the LIDT. Because past efforts have focused primarily on maximizing LIDT, there is a growing need to design and fabricate optical components that specifically optimize resistance to damage growth.

Thermally induced stresses present an additional challenge, particularly in lasers operating at high average power. Even small levels of absorption can lead to the accumulation of stress through thermal gradients and mismatches in thermal expansion coefficients, leading to surface deformation, crack formation, delamination, and fatigue. Addressing these effects requires design strategies that minimize energy localization, redistribute stress, and use interface engineering to suppress damage-prone features while preserving optical functionality.

Meeting these component-level demands places stringent requirements on the constituent materials. For defect-free, ideal materials, key intrinsic optical properties include wide bandgaps, minimal linear absorption and scattering, low Kerr nonlinearity to suppress self-focusing, and reduced multiphoton absorption. Thermomechanical requirements include high melting temperature, low thermal expansion, high elastic moduli, and sufficient fracture toughness to withstand thermal and mechanical loading. Long-term performance also requires thermochemical stability, including resistance to phase transformation, segregation, and irradiation-induced degradation.

In practice, ideal material properties are undermined by a hierarchy of defects present across multiple scales. At the atomic level, native point defects, impurity complexes, and color centers introduce sub-bandgap states that increase optical absorption and seed the initial damage. This intrinsic instability is compounded at the nanoscale by features such as polyamorphism and compositional fluctuations, which create spatially heterogeneous responses to laser energy. At larger length scales, microstructural defects including microcracks, voids, and grain boundaries act as stress concentrators and energy localization hot spots. Ultimately, these collective imperfections can trigger defect-driven damage amplification, runaway absorption, and catastrophic failure, especially under the cumulative stress of repeated irradiation.

A useful benchmark for assessing potential improvements is the comparison between bulk materials and fabricated optical coatings. Fused silica (SiO_2) provides a representative example. The damage threshold of the best-performing silica coatings is typically only about 10–40% of that of the highest-quality bulk material, depending on irradiation conditions. This gap highlights the extent to which fabrication-induced defects currently limit performance and provides a rough estimate of the improvement that may be achievable through advances in materials processing and defect control. Development of new materials systems, including compositionally complex dielectrics and alternative coating architectures, may further improve performance, particularly for high-index materials that inherently possess smaller bandgaps and lower damage thresholds.

Surface condition and environmental exposure represent additional critical factors governing component performance. Surface contamination, adsorbates, and chemical modification can introduce localized absorption and field enhancement that alter damage thresholds and incubation behavior. Interactions with ambient gases, residual contaminants, and laser-generated reaction products can further influence surface chemistry and stability under irradiation. Mitigation strategies must therefore account for the specific operating environment, including laser wavelength, pulse duration, repetition rate, and atmospheric conditions. For example, ultraviolet or ultrashort laser irradiation of certain dielectric materials can trigger photochemical reactions that degrade surface quality or introduce localized contamination from volatile organic species. Some of these effects remain poorly understood and effective mitigation strategies are yet to be developed.

Examining specific system requirements further illustrates the scale of the challenge. For example, the proposed 20-fs NSF OPAL laser system requires optics capable of sustaining damage growth thresholds above roughly 0.35 J/cm^2, providing a factor-of-two safety margin above the operating fluence. Such performance has been demonstrated in a small mirror but has not yet been achieved using scalable coating processes suitable for large optics. For pulse compression gratings, gold gratings offer theoretical thresholds near 0.3 J/cm^2, although existing systems typically operate at significantly lower fluences (~0.1 J/cm^2). Emerging mixed metal–dielectric grating concepts may help extend these limits.

Similarly demanding conditions arise in ns-class ultraviolet laser systems envisioned for future inertial fusion energy facilities, where target fluences approach ~4 J/cm^2. Recent experiments on small samples have demonstrated damage growth thresholds approaching this level using Al_2O_3 as a high-index material, but these results have not yet been validated under realistic operating conditions or extended multiyear exposure. Achieving reliable performance under such conditions remains a significant challenge.

In conclusion, the performance of optical components represents the fundamental limiting factor in high-power laser system design and operation. To avoid the prohibitive cost and downtime associated with frequent replacement of damaged optics, laser systems are typically operated well below their theoretical maximum output. Improving the damage resistance of optical materials and components would therefore have a direct and transformative impact, enabling higher operating fluences. In turn, this would allow the development of smaller, more cost-effective optical components and lead to more compact, efficient, and powerful laser systems for future scientific, industrial, national security, and energy applications.

3. Mechanisms and Mitigation of Laser Damage

The mechanisms of laser-induced damage have been recognized as a high-priority research topic since the early days of laser development. Following the establishment of the laser group at the Air Force Weapons Laboratory in 1962, the first open-literature publications on laser damage appeared in 1964, including presentations at the Optical Society of America (OSA) spring meeting by Mike Hercher (University of Rochester) and a paper in *Applied Physics Letters* by Connie Giuliano and Bob Hellwarth (Hughes Research Laboratories). A sufficiently large research community emerged soon thereafter, leading to the first Laser Damage Conferences organized at the National Bureau of Standards (presently National Institute of Standards and Technology) in Boulder, Colorado (June 1969) and in Leningrad, Soviet Union (October 1969).

Despite early optimism that the laser damage problem will be a minor issue in laser development, the ensuing nearly 60 years of research was a continuous struggle to improve the damage performance of components and laser output. This effort was supported by the development of theoretical frameworks describing damage initiation under different excitation conditions and in the presence of various material defects. However, the operational requirements of successive generations of laser systems have consistently demanded higher power and energy, placing increasing demands on the damage thresholds of optical components.

Today, laser systems operate in regimes where further substantial improvements will require optical materials that exhibit performance approaching that of ideal, defect-free materials. Progress in extending the performance and lifetime of optical components is therefore fundamentally limited by incomplete understanding of laser interactions with defects at the atomic level. There is a critical need to establish how specific classes of defects and microstructural features respond to different irradiation conditions, and how these responses control distinct damage scenarios, including damage initiation, incubation and fatigue under multi-pulse irradiation, and long-term degradation during extended operation.

The development of the advanced optical component designs currently available, such as multilayer dielectric coatings and gratings, has been the result of rapid technological evolution in fabrication methods, particularly physical vapor deposition techniques. The resulting materials are produced through optimization of multiple fabrication parameters to achieve the required optical and thermomechanical properties. However, the influence of the defects introduced during the fabrication on laser damage performance remains difficult to assess.

Advanced materials characterization, both prior to laser exposure and *in situ*/*in operando*, is essential for linking the laser damage behavior to underlying structural and chemical changes in the constituent optical material components. Material characterization techniques, such as photothermal absorption measurements, X-ray photoelectron spectroscopy, small-angle X-ray scattering, Raman and fluorescence spectroscopy, transmission electron microscopy, and atom probe tomography, can provide complementary insights into defect populations, chemical states, nanoscale heterogeneities, and irradiation-induced structural changes. Applied systematically, these methods could clarify the evolution of defect structures associated with performance degradation or catastrophic failure. Time-resolved probing of material response to laser excitation below the damage threshold may be an effective way to reveal ultrafast processes associated with the initiation of laser damage. Pump–probe optical spectroscopy can track excited-state lifetimes, carrier excitation and relaxation pathways, as well as defect activation under different excitation conditions (pulse duration, laser wavelength, pulse energy, repetition rate). Interferometric methods can yield valuable information on the transient refractive index changes and stress evolution, while ultrafast X-ray and electron diffraction provide direct access to nonthermal and thermal lattice dynamics, phase transformations, and the emergence of structural disorder during and immediately following laser excitation. While recognizing that there is a varying degree of difficulty in implementing these techniques for the study of optical materials fabricated with different methods, they can help bridge the gap between electronic excitation and material response, providing critical input for advancing the mechanistic understanding of laser damage.

Computational modeling plays a central role in integrating the results of experimental characterization into a unified mechanistic understanding of laser damage phenomena. Modeling can help identify the origin of defects in as-fabricated materials and predict the types of defects that may form under specific fabrication conditions, such as variations in oxygen content, ion energy, or the presence of organic contaminants. A range of individual modeling methods span the full cascade of processes involved in laser–matter interaction, from laser absorption, excited-state dynamics, and nonthermal atomic motion described by time-dependent density functional theory and *ab initio* molecular dynamics, to thermalization, energy transport, defect generation, and structural transformations addressed by large-scale molecular dynamics and multiphase hydrodynamic models. Long-term microstructural evolution, including defect migration, annihilation, and potential damage recovery, can be investigated using kinetic Monte Carlo, phase-field methods, and related mesoscale approaches. A critical need is the closer integration of modeling methods across these scales, into a coherent multiscale framework enabling systematic transfer of physical mechanisms, parameters, and constitutive relationships from lower-level descriptions to higher-level models. Rather than treating individual modeling approaches as loosely connected tools, predictive capability requires consistent coupling, coordinated model development, and cross-scale validation between electronic, atomistic, mesoscopic, and continuum models.

In conclusion, advancing the fundamental understanding of laser damage, its underlying causes, and its implications for optical material performance requires a transition from predominantly empirical optimization toward approaches guided by mechanistic understanding. This necessitates a dual experimental approach: testing realistic samples in parallel with engineered ones that have intentionally controlled defects. This strategy allows for the systematic isolation of individual variables to pinpoint their specific roles in initiating damage. The effort must be integrated with a three-pronged approach that combines (i) advanced *in-situ* diagnostic techniques during fabrication, (ii) *in-situ* time-resolved probing and *ex-situ* characterization of laser damage initiation and growth, and (iii) computational modeling of the entire damage pathway from quantum-level interactions to macroscopic failure. By establishing clear quantitative correlations between material properties and laser damage thresholds, researchers can identify causal relationships, a process significantly accelerated by using “component proxies” for high-throughput testing. By pursuing this integrated strategy, the field can move toward a predictive, cause-and-effect understanding of laser damage and enable the design of more resilient optical materials.

4. Materials Design for High-Power Laser Applications

The advancement of high-power laser systems has been constrained by insufficient progress in optical materials over the past two decades. A central challenge lies in the dual requirement of employing a limited set of materials with favorable intrinsic properties, such as a wide bandgap and strong thermomechanical stability, while minimizing a diverse population of defects that degrade performance. Many of these defects originate from fabrication processes or develop under operational conditions. As a result, the reliability and lifetime of optical components, which must operate near their damage thresholds, have become a primary limiting factor necessitating a coordinated effort in both basic and applied research. Basic research is essential for developing a fundamental understanding of material behavior under high-power, high-energy laser irradiation, particularly in extreme environments relevant to national security applications. Such foundational work provides the scientific basis for future technological advances, while complementary applied research is needed to translate emerging insights into useful materials, devices, and methods capable of meeting specific laser system requirements.

An important aspect of this approach is physics-based and data-driven materials discovery and selection that combines modeling and experiment. High-throughput density functional theory calculations, machine learning methods, and targeted experimental screening enable efficient exploration of the high-dimensional composition space of multi-component oxide- and fluoride-based ceramic systems, as well as other wide bandgap materials such as nitrides, carbides, and diamond-based structures. These approaches support rapid evaluation of key properties, including bandgap and optical absorption, nonlinear optical response, thermal expansion, and defect formation energies. When coupled with mechanistic insights from laser damage studies, such workflows enable identification of candidate materials that balance optical performance with damage resistance and long-term stability.

Defect mitigation represents a second central element of materials design for high-power laser applications. Rather than treating defects solely as unavoidable limitations, emerging strategies seek to engineer microstructural architectures and defect configurations that exhibit enhanced resistance to laser damage and, in some cases, self-healing behavior, including the deliberate incorporation of features that act as sinks for laser-generated point defects and defect clusters. Large-scale atomistic simulations and continuum-level modeling can provide guidance on how defect distributions, interfaces, and phase structures influence energy localization, damage initiation, and recovery processes, as well as defect migration and annihilation pathways. These predictions inform experimental efforts aimed at realizing defect-tolerant or damage-resistant microstructures through controlled synthesis and processing.

Surface condition and environmental stability constitute a third critical dimension of materials design. In many real-world high-power laser applications, damage initiation is strongly influenced by surface states, contamination, and interactions with the surrounding environment. Systematic evaluation of material-specific sensitivity to surface-driven damage, including electronic structure calculations and surface spectroscopy, can help identify vulnerable chemical and structural motifs. Studies of interactions between material surfaces and the surrounding environment under conditions of high-intensity laser irradiation can further clarify the roles of adsorption, oxidation, and plasma formation in damage initiation. These insights support the development of mitigation strategies such as surface passivation, protective coatings, and engineered interface layers.

In conclusion, effective material design for high-power laser applications can no longer be based on a linear process. Instead, a dynamic, iterative framework that involves a synergistic loop between foundational science and practical high-throughput testing is required. It begins with establishing a deep mechanistic understanding, *i.e.*, a complete physical picture of how and why materials fail under laser irradiation. This knowledge can fuel predictive models to guide the discovery of new material compositions, microstructures and optical designs. The critical bottleneck of slow and costly testing is then overcome by the "component proxy" concept. By using simplified test structures, researchers can rapidly gather the essential performance data needed to validate and refine their predictive models. This will create a powerful feedback cycle: proxy data improve the models, and the improved models suggest novel materials and designs that can be quickly tested as new proxies. It is this closed-loop strategy, bridging fundamental theory with rapid, practical validation, that can truly accelerate material design for high-power, high-energy laser applications to enable the efficient development of next-generation optics with the exceptional power handling capability and reliability the field demands.

5. Fabrication of Large Aperture Optical Materials and Components

One of the primary obstacles to developing next-generation high-power laser systems is the immense difficulty of scaling the manufacturing of high-performance optical components from the laboratory to the facility level. This overarching challenge highlights a fundamental gap between current fabrication capabilities, which often rely on artisan-like expertise, and the urgent need for a predictive, science-based manufacturing paradigm capable of producing meter-scale optics that meet specifications reliably and affordably. To bridge this gap, fabrication must transition to rely on scientifically informed strategies guided by a mechanistic understanding of material performance rather than on empirically optimized workflows.

This comprehensive approach requires that new synthesis routes and processing protocols be directly informed by the physical and chemical factors governing material stability. A cornerstone to this strategy is the development of online (during fabrication) material characterization tools that would enable accurate control of the as built material properties. Offline characterization of the material performance would enable the optimization of the fabrication processes towards meeting predetermined performance specifications. Computational modeling can assist by simulating critical processes like microstructural evolution and defect incorporation. Rather than attempting to model entire multistep workflows, the physics-based modeling should focus on the key stages that control final quality. The wealth of computational and empirical data, in turn, can be used to train machine learning-based surrogate models—computationally efficient approximations of complex physics that make the digital twin concept feasible. These surrogates can then rapidly explore the high-dimensional processing space, guiding experimental efforts toward the most promising and efficient manufacturing conditions. By incorporating uncertainty quantification, these predictive tools provide a foundation for robust, reproducible manufacturing protocols.

Scalability challenges are prominent across all critical optical components. For gratings and coatings, maintaining atomic-scale material quality over macroscopic dimensions remains a central difficulty. Deposition processes capable of producing exceptional films on small substrates face significant hurdles when applied to meter-scale optics, where contamination control, temperature uniformity, and internal stress management become increasingly demanding. Success requires moving beyond empirical tuning toward a predictive science of fabrication, employing strategies such as interface engineering and compositional grading to control stress, suppress field enhancements, and ensure thermomechanical compatibility across large areas.

Similarly, for optical crystals, the primary limitation is the difficulty of growing large, meter-scale single crystals with perfect optical uniformity. This constraint often necessitates alternative approaches, such as bonding smaller crystals, which introduces additional challenges in forming flawless and durable interfaces. A science-driven approach can guide the development of innovative solutions, including transparent glass ceramics that combine favorable optical properties with superior mechanical strength and thermal shock resistance, potentially enabling more scalable fabrication than conventional optical glasses.

In conclusion, the component-specific issues in gratings, crystals, and coatings are all strongly affected by two main issues: (i) the ability to control defects during fabrication and (ii) the central challenge of scaling. The progress is no longer limited by basic theoretical understanding but by the practical, engineering-level difficulty of translating material science breakthroughs into reliable, large-scale manufacturing. Without a focused effort to develop a predictive science of fabrication—integrating mechanistic understanding, multiscale modeling, and *in situ* characterization—the construction of future high-power laser facilities will remain constrained by the performance limits of components that can be produced affordably and reliably at scale.

6. Digital Twins and Uncertainty Quantification

As outlined above, there is a need for a strategic shift away from empirical, trial-and-error methods toward a more science-based, predictive approach for designing optical materials and components. Realizing this strategic vision is paramount because the reliable fabrication of materials for high-power laser systems currently remains a significant challenge. Present manufacturing processes—typically involving multiple, complex heating and deposition steps—are frequently developed by trial-and-error, with successful approaches residing only in the institutional knowledge of specialists. This reliance on artisan-like expertise introduces significant manufacturing variability where batch-to-batch differences and process drift undermine reproducibility and slow down root-cause analysis. Consequently, the materials community urgently needs to transition to a physics-based methodology that provides a deep understanding of each step in the manufacturing process. While decades of investment have produced massive datasets from advanced characterization techniques, this information is often disconnected from the manufacturing process, leaving a gap where tools for multi-strategy reasoning are needed to make accurate inferences and demonstrate fabrication in a consistently repeatable manner.

To transition from a heuristic approach to a scientific one, the central aim is to achieve manufacturing reproducibility for specific, critical material properties that dictate performance, such as optical damage threshold, absorption coefficients, and thermomechanical stability. This requires quantifying the link between processing conditions and the resulting material microstructure. Future research must therefore clearly identify which properties will be targeted for reproducibility and articulate how proposed methods will provide the scientific insights needed to control these outcomes at scale. To formalize this challenge, the fabrication and use of a high-power laser optic can be framed as a partially observed controlled stochastic process. This framework highlights three core probabilistic links that must be addressed: first, how design and manufacturing parameters determine the initial state of the optical material; second, how that state evolves under laser pulses to produce degradation or damage; and third, how the true, hidden state of the optic relates to limited and noisy measurements.

Addressing these links necessitates organizing research opportunities into two complementary thrusts. The first thrust is to develop predictive “digital twins” of optical components – physics-informed, data-integrated models capable of capturing the relationships between processing, material structure, and performance. These models should distinguish between two types of uncertainty: inherent, unavoidable randomness in a process versus uncertainty that stems from a simple lack of knowledge. By identifying what we do not know, these models can guide investment in new experiments for the greatest and most efficient information gain. The second thrust is to use AI assistants to accelerate the entire scientific discovery workflow. The long-term vision is a self-improving "discovery flywheel," where an AI assistant suggests an experiment, learns from the results, and then recommends the next most informative experiment to perform.

In conclusion, achieving reproducible, high-performance optical materials for high-power laser systems requires a transition to a predictive, physics-based framework that explicitly accounts for variability and uncertainty in fabrication and operation. Digital twins, combined with uncertainty quantification, provide the means to link processing conditions, material structure, and performance under laser irradiation. By integrating modeling, advanced characterization, and data-driven methods, these approaches can identify key knowledge gaps, guide targeted experiments, and enable more reliable manufacturing. Realizing this capability will require coordinated investments in data infrastructure, interpretable AI-assisted workflows, and experimental platforms that close the loop between prediction and validation, ultimately supporting scalable production of optical components with predictable performance and lifetime.

7. Pulse Compression and Spectral Beam Combining Gratings

Diffraction gratings are essential components in high-energy, high-power lasers in two key areas: pulse compression for high peak intensity lasers and spectral beam combining for high average power lasers. These gratings typically consist of a top layer comprised of evenly spaced, nanostructured lines (pillars) which produce wavelength-dependent diffraction and dispersion of the incident light. There are three general classes of gratings. The first are metal gratings, which were used in the early demonstrations of laser pulse compression, a technique recognized by the 2018 Nobel Prize in Physics. A key advantage of metal gratings is their large spectral bandwidth, which can support compression of pulses to durations below 10 fs. However, the metal gratings exhibit strong absorption of the laser light, which limits the maximum fluence they can sustain before melting. This limitation is overcome by multilayer dielectric gratings that consist entirely of dielectric materials. These gratings exhibit very low absorption and are therefore better suited for high energy or high average power applications. Their drawback is a significantly narrower spectral bandwidth, typically limiting their use to compression of pulses longer than about 200 fs. An intermediate approach that has been proposed and partially explored involves hybrid metal-dielectric gratings, in which a metal reflector is combined with a small number (or none) of dielectric coating pairs and a dielectric pillar structure on the surface. This design reduces absorption losses while providing increased spectral bandwidth, enabling compression of pulses to durations of about 20 fs.

The damage performance of gratings is governed by two primary failure mechanisms: localized "hot spots" inherent to any grating design, which govern the damage initiation threshold of dielectric pillars, and absorption by the material, which governs the damage threshold of spectral beam combining gratings and gold gratings. For pulse compression gratings, decreasing the pulse duration increases the peak intensity and consequently lowers the damage threshold of gratings with dielectric pillars. In addition, the nanofabrication methods used to produce the grating structures (typically involving reactive ion etching) can introduce defects and structural damage in the top pillar layer, further reducing damage resistance.

In contrast, the damage threshold of metal gratings is governed by the total absorbed energy, resulting in relatively weak dependence on laser pulse duration. As a result, gold gratings can exhibit higher damage thresholds for shorter pulses, which has facilitated their use in current-generation ultrashort pulse laser systems. However, due to their large surface area and nanoscale structuring, metal gratings are particularly susceptible to contamination and long-term material fatigue. Moreover, their complex geometry makes them especially sensitive to the scalability challenges discussed in the previous sections.

Several strategies have been identified to achieve significant progress in grating technologies based on dielectric pillars. One of the most important directions is the improvement of coating materials using the science-based, predictive approaches discussed in the previous section. In addition, the development and optimization of new high-index material mixtures for grating fabrication could improve both damage thresholds and spectral bandwidth. The nanofabrication processes used to produce grating structures often introduce detrimental material modifications and contamination that degrade performance. This issue arises in part because grating fabrication technologies were originally adapted from the microelectronics industry more than 40 years ago and were not developed for fabrication of optical components exposed to high intensity or high average power laser irradiation. At the same time, modern semiconductor etching techniques are suitable for many high-index materials of interest for next-generation gratings, such as hafnia, scandia, yttria, and their mixtures with silica, but these methods have not yet been successfully translated to fabrication of meter-scale optical components. For ultrashort-pulse compression, bandwidth requirements necessitate the use of such high-index materials as higher-performance alternatives to current-generation all-metal gratings. Additionally, existing gratings cleaning procedures must be compatible with these materials, or new approaches must be developed. Realizing mixed metal-dielectric gratings requires a comprehensive development roadmap that includes understanding the intrinsic properties of candidate material mixtures, establishing etching and cleaning protocols that minimize process-induced defects, and addressing the engineering challenges associated with scaling.

Finally, while iteratively improving the coating material quality is likely to be the primary method by which gratings see a substantial performance increase, there are other areas that can be explored and may lead to further improvements. These include new grating structure geometries designed to shift peak electric field intensification away from the line material, which could increase the grating LIDT by approximately 30%. Another opportunity lies in reducing etch-induced defects through improved cleaning procedures or alternative fabrication routes. For example, fabrication with additive manufacturing approaches, such as the damascene process, avoids direct etching of the grating structure and could provide improvements of roughly 10–50%, depending on the coating deposition method. Importantly, these improvements are largely multiplicative with gains achieved through improved coating materials. When combined, they could enable an overall two- to four-fold increase in grating damage performance. In the long term, new approaches to pulse compression may emerge as viable alternatives, including plasma- or gas-based gratings.

In conclusion, advancing grating technologies for next-generation high-power laser systems requires a paradigm shift away from the current proprietary, institution-centric model. Achieving the necessary power scaling and operational reliability demands a synergistic effort that fosters broader engagement from the basic research community and invests in innovative fabrication methods. This transition is currently hindered in the United States by significant structural barriers, including the limited public disclosure of fabrication techniques, restricted access to meter-scale patterning tools, and the lack of publicly available reactive ion beam etching systems. Overcoming these obstacles is essential to unlocking future progress in the field.

8. Summary

This workshop report outlines a coordinated strategy to overcome the primary obstacle limiting the advancement of high-power, high-energy laser systems: the performance and reliability of their optical materials and components. The scope of the workshop was intentionally focused on passive optical components—such as mirrors, coatings, and gratings—and did not include the development of laser gain media (host materials). The workshop concluded that progress is primarily constrained not by laser physics but by the immense difficulty of manufacturing scalable optics with consistent quality. Current fabrication often relies on inconsistent, "artisan-like" expertise, leading to variability and defects that cause performance degradation. This is compounded by the fundamental scientific challenge that these engineered materials are inherently in non-equilibrium, thermodynamically unstable states, making them prone to failure.

The strategy outlined in this report calls for a fundamental shift from an empirical, trial-and-error approach toward a predictive, science-based framework for materials design and manufacturing. This framework rests on two key pillars. The first is to achieve a deep mechanistic understanding of material failure by integrating systematic experimental characterization with advanced multiscale modeling. The second is to establish clear, application-driven performance metrics from the outset—a mandate to "define good enough"—to focus research and prevent an unfocused search for perfection.

Ultimately, these pillars must be unified within a cohesive "closed-loop discovery flywheel" powered by modern computational tools. In this paradigm, high-fidelity "digital twins"—virtual models that simulate component's entire lifecycle from fabrication to failure—are used to guide materials selection and process optimization. This iterative cycle, accelerated by high-throughput testing, is further enhanced by agentic AI systems capable of orchestrating the entire workflow, from synthesizing literature to recommending the next most informative experiment.

By systematically integrating mechanistic understanding, predictive digital twins, and AI-driven discovery, the approaches described in this report define a coherent pathway toward optical components with predictable performance and extended lifetimes. The workshop underscored that success is contingent on a unified, collaborative strategy between academia, national laboratories, and industry, creating the foundation required for sustained power scaling in next-generation laser systems.

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