

Review

Ultrafast Optical Field Engineering for Laser Micro- and Nanofabrication

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Abstract

Ultrafast laser micro- and nanofabrication has emerged as a powerful platform for precision manufacturing due to the unique capability of femtosecond pulses to provide highly localized energy deposition and controlled laser–matter interactions. However, conventional scanning-based processing approaches remain limited by a fundamental trade-off between spatial resolution and fabrication throughput. Recent advances in ultrafast optical field engineering provide new strategies for overcoming these limitations through coordinated control of temporal, spatial, and spatiotemporal characteristics of ultrashort laser fields. This review presents recent developments in ultrafast optical field engineering for laser micro- and nanofabrication, covering programmable pulse shaping, spatiotemporal control, spatial light modulation, structured light approaches, holographic methods, and hybrid optical architectures. The operating principles of these technologies are discussed together with their influence on energy deposition, processing accuracy, scalability, and manufacturing efficiency. Particular attention is given to applications in high-throughput surface structuring, parallel microfabrication, three-dimensional processing, photonic device fabrication, and functional material modification. Different optical architectures are compared in terms of flexibility, optical efficiency, power-handling capability, and industrial applicability. The review highlights the transition from conventional single-spot processing toward adaptive, parallel, and programmable optical manufacturing systems, emphasizing integrated control of ultrafast optical fields as a key direction for future laser fabrication.

Keywords: ultrafast laser processing; optical field engineering; femtosecond pulse shaping; spatial light modulation; structured light; adaptive optics; laser micro- and nanofabrication

1. Introduction

Ultrafast optical technologies have evolved from picosecond to femtosecond laser sources, significantly expanding the capabilities of precise energy delivery and control of nonlinear laser–matter interactions. Building on these developments, ultrafast optical field engineering has become an important direction in advancing laser micro- and nanofabrication, providing precise control over the temporal, spatial, and spatiotemporal characteristics of ultrashort laser fields [1]. These approaches open new opportunities for controlling material response and fabricating functional structures in metals, dielectrics, semiconductors, and emerging two-dimensional materials. Further progress in ultrafast laser technologies enables the transition from fundamental studies of nonlinear laser–matter interactions toward industrial fabrication of functional surfaces, photonic devices, and three-dimensional microstructures [2]. In particular, the integration of advanced optical



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control with laser processing promotes the development of integrated photonic structures and hybrid functional systems with complex geometries and enhanced performance [3].

A major development direction is the improvement of precision control over laser processing at micro- and nanoscale. This includes both fundamental aspects of ultrashort pulse interaction with matter and engineering strategies for controlling the temporal, spatial, and spatiotemporal distribution of optical fields in laser processing systems [4]. Recent studies demonstrate the possibility of forming complex three-dimensional structures and devices with high functionality, including electrochemical systems and energy-efficient materials [5]. At the same time, advances in direct laser processing have significantly expanded the range of achievable architectures, including multilayer, volumetric, and functional structures [6].

Despite these advances, most current technological approaches are still based on sequential patterning using a tightly focused laser spot scanned across the sample in a beam delivery system. Although such methods provide high positioning accuracy, they are fundamentally limited by the trade-off between spatial resolution and processing throughput. When the focal spot size decreases and resolution requirements increase, fabrication speed drops significantly, which strongly limits scalability for industrial applications [7]. Even with optimized irradiation conditions and high-power laser sources, overall efficiency remains constrained by the sequential nature of beam delivery and scanning mechanisms rather than by the laser pulse duration itself [8].

Additional limitations arise from the challenges of high-precision fabrication of complex structures, including the need to maintain stable focusing conditions, control ablation depth, and avoid defects caused by non-uniform energy distribution and optical field inhomogeneity in the processing region [9]. Reduced reproducibility may occur when transitioning toward three-dimensional or multiscale architectures, indicating the need for improved strategies for controlling laser-matter interaction and energy deposition dynamics [10].

One of the most promising routes to overcome these limitations is the transition from sequential scanning toward parallel and adaptive optical field engineering approaches, enabling simultaneous generation of multiple structural features and tailored energy distributions [11]. Such strategies rely on multi-focal, multi-beam, and structured-field configurations that enhance processing throughput while maintaining high spatial precision. These technologies include both programmable optical systems and engineered passive optical architectures for controlling laser intensity and phase distributions [12].

In this context, spatial light modulation plays an increasingly important role by enabling dynamic control of the optical field phase and amplitude in laser processing systems. Spatial light modulators and holographic techniques allow the generation of complex intensity distributions in the processing plane and support parallel structuring strategies [13]. Further developments have resulted in hybrid systems combining multiple beam-shaping approaches, adaptive optical elements, and computational optimization methods to improve flexibility and processing performance [14].

Modern ultrafast laser systems increasingly rely on programmable optical components that enable controlled manipulation of laser fields beyond conventional beam delivery concepts. Mask-based projection systems, spatial modulation techniques, and holographic approaches provide dynamic modification of irradiation patterns and enable multi-image and three-dimensional field generation with improved adaptability [15,16].

Significant progress has also been achieved through holographic methods and Fourier optical transformations for generating multi-spot intensity distributions and complex three-dimensional optical fields, enabling high-speed parallel microfabrication [17,18]. At the same time, efficient optical design, power management, and integration into industrial laser platforms remain essential factors for practical implementation [19].

The field of optical field engineering is rapidly advancing through the development of new algorithms, materials, and device architectures, including high-speed phase and amplitude modulators for programmable photonic systems [20]. Recent progress in programmable photonics has enabled advanced pulse shaping and dynamic control of ultrafast optical fields, while projection architectures based on spatial–temporal focusing have increased fabrication throughput without sacrificing submicrometer resolution [21,22]. Adaptive optical systems further improve processing stability by enabling real-time correction of focusing conditions and optical field variations during fabrication [23].

Current research in ultrafast laser micro- and nanofabrication increasingly focuses on advanced optical field control strategies that combine high-throughput processing with precise manipulation of spatial, temporal, and spatiotemporal laser characteristics [24]. These approaches include programmable pulse shaping, holographic field synthesis, spatial light modulation, structured illumination, and hybrid optical architectures, enabling parallel fabrication, three-dimensional processing, and improved control over laser–matter interactions [25,26].

This review summarizes recent advances in ultrafast optical field engineering for laser micro- and nanofabrication, covering temporal pulse shaping, spatiotemporal control, spatial beam shaping, holographic methods, and hybrid optical architectures. Available review articles have focused on specific ultrafast laser processing techniques, beam-shaping methods, and application-oriented developments. In this review, ultrafast optical field engineering is presented as an integrated framework that unifies the control of amplitude, phase, polarization, temporal, and spatiotemporal characteristics of ultrafast laser fields across multiple optical domains. Particular emphasis is placed on the evolution from passive optical elements toward programmable and hybrid multi-domain architectures, and on their influence on energy deposition, nonlinear material response, processing accuracy, and fabrication throughput. The advantages, limitations, and technological trade-offs of different optical-field engineering strategies are analyzed in relation to scalability, industrial implementation, and future developments in ultrafast laser manufacturing.

2. Spatiotemporal Pulse Shaping and Ultrafast Optical Field Engineering

The ability to tailor the temporal and spectral characteristics of femtosecond laser pulses has become one of the important enabling technologies for modern ultrafast photonics and precision laser processing. Unlike conventional beam shaping, which primarily modifies the spatial intensity distribution, pulse shaping provides deterministic control over the temporal envelope, spectral phase, and frequency-dependent properties of ultra-short optical fields. When combined with spatial, polarization, and wavefront control, these approaches enable comprehensive spatiotemporal engineering of laser fields, allowing optimization of nonlinear light–matter interactions, selective excitation of physical processes, and improved laser processing efficiency.

Early pulse-shaping techniques relied primarily on Fourier-domain spectral modulation using spatial light modulators positioned in dispersive optical systems. During the last decade, these approaches have evolved toward programmable photonic platforms, adaptive optical systems, and metasurface-based architectures capable of extending pulse control toward simultaneous manipulation of spatial, temporal, and polarization degrees of freedom. Recent reviews summarize the rapid progress of intense femtosecond pulse shaping and its transition from laboratory coherent control experiments toward practical engineering applications involving spatiotemporal optical field manipulation and laser manufacturing [27]. This evolution increases the flexibility of ultrafast field control while introducing new challenges related to optical complexity, calibration requirements, and scalability.

A fundamental trend is the transition from purely temporal pulse modulation to complete spatiotemporal engineering of ultrashort optical fields. Rather than controlling only pulse duration or spectral phase, modern systems generate arbitrary temporal profiles, programmable pulse sequences, and spatially dependent temporal distributions. Targeted synthesis of complex temporal pulse profiles has recently been demonstrated using programmable optimization algorithms, providing precise control over excitation dynamics in ultrafast experiments [28]. Similar developments have enabled high-repetition-rate pulse shaping of spectrally broadened ytterbium femtosecond lasers while maintaining excellent temporal stability, which is particularly attractive for industrial laser systems operating at high average powers [29].

Recent advances increasingly exploit artificial intelligence and physics-informed optimization for pulse synthesis. Deep-learning-assisted inverse design has demonstrated efficient engineering of spectro-temporal optical states while significantly reducing computational complexity associated with conventional optimization algorithms [30]. Complementary numerical simulation approaches enable modeling of linear and nonlinear optical propagation, supporting optimization of pulse-shaping strategies before experimental implementation [31]. An example of numerical simulation and characterization of femtosecond laser pulses using a virtual optical setup is shown in Figure 1 [31]. Such computational approaches are particularly relevant for ultrafast laser manufacturing, where optimization of pulse parameters becomes increasingly important for controlling nonlinear energy deposition and material response.

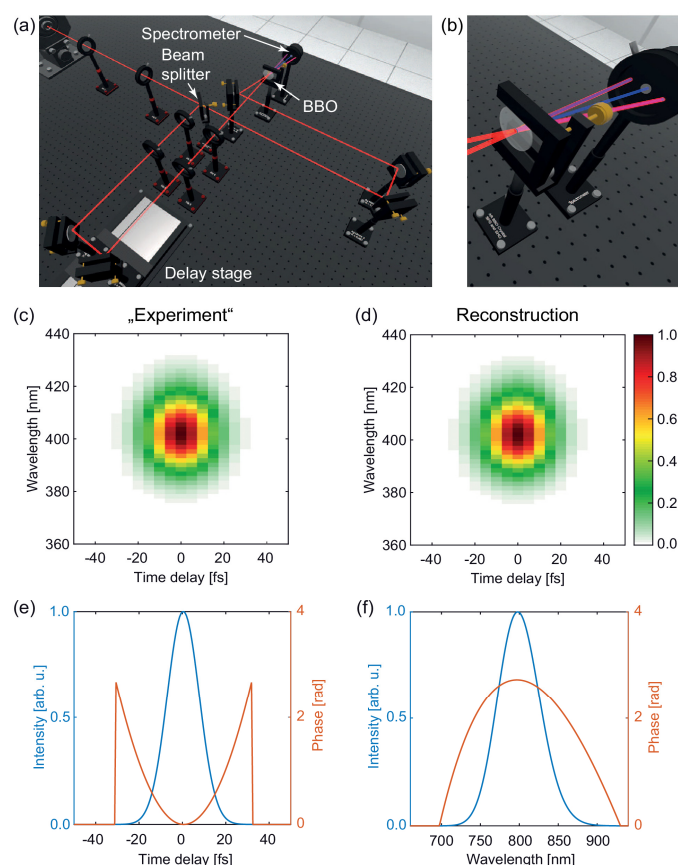


Figure 1. Numerical simulation and characterization of femtosecond laser pulses using a virtual optical setup. (a) Mach-Zehnder interferometer with second-harmonic generation in a β -barium borate crystal. (b) Spectral detection of the generated signal. (c,d) Simulated and reconstructed pulse-characterization traces. (e,f) Retrieved temporal and spectral intensity and phase characteristics [31].

An important direction concerns compact optical elements that can complement or partially replace conventional Fourier pulse shapers. Dielectric and semiconductor metasurfaces provide simultaneous control of spectral phase, polarization, and wavefront within ultrathin optical components. Dielectric metasurfaces have demonstrated direct ultrafast pulse shaping with subwavelength optical elements, opening opportunities for miniaturized pulse-control systems [32]. More recently, semiconductor Huygens metasurfaces have extended these capabilities by enabling programmable femtosecond pulse shaping with high efficiency and reduced optical losses [33]. The operating principle of metasurface-based pulse shaping, in which spectral components of an ultrashort pulse are spatially separated, individually modified, and recombined to obtain controlled temporal waveforms, is illustrated in Figure 2. In parallel with metasurface-based concepts, alternative optical approaches based on reflective elements under grazing-incidence conditions have been demonstrated for femtosecond pulse shaping, offering a simplified optical scheme [34]. Compared with conventional Fourier pulse shapers, metasurface approaches provide compact and multifunctional solutions, with efficiency, bandwidth control, and fabrication technologies remaining active research directions.

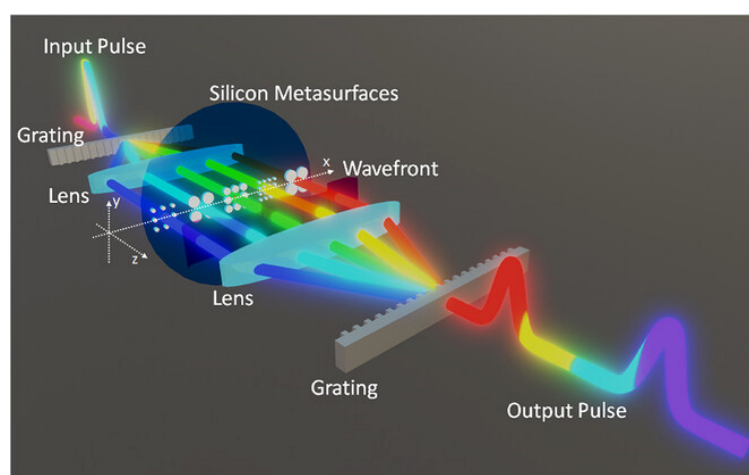


Figure 2. Conceptual principle of femtosecond pulse shaping using a semiconductor Huygens metasurface in a Fourier optical configuration. The input pulse is spectrally separated by a diffraction grating, after which individual spectral components pass through metasurface elements with different phase and amplitude characteristics. The different colors represent discrete spectral components for illustration purposes, while the actual pulse spectrum is continuous. Control of the spectral response of the metasurface enables modification of the temporal pulse profile after recombination of the spectral components [33].

Beyond temporal modulation alone, increasing attention is devoted to complete spatiotemporal control of ultrashort laser fields. Simultaneous shaping of spatial and temporal characteristics allows optimization of energy localization, nonlinear interaction efficiency, and propagation dynamics in complex optical environments. Such approaches have been successfully demonstrated in biomedical laser applications, including targeted gene transfection using combined temporal and spatial femtosecond laser shaping, where improved delivery efficiency was achieved while minimizing collateral damage [35]. Similar concepts are being explored for industrial processing, including battery manufacturing, where combined spatial and temporal pulse optimization enhances energy deposition and processing throughput [36].

Spatiotemporal beam engineering has also enabled the generation of structured electromagnetic fields for advanced laser–plasma interaction studies. Direct experimental observation of laser wakefields generated by structured light demonstrates how tailored

optical fields can manipulate relativistic plasma dynamics beyond the capabilities of conventional Gaussian beams [37]. Complementary single-shot metrology techniques now provide complete characterization of spatiotemporal laser fields in relativistic plasma optics, enabling experimental validation of increasingly sophisticated pulse-shaping schemes [38].

Another rapidly developing direction concerns manipulation of additional optical degrees of freedom. Polarization shaping of free-electron laser pulses has recently enabled complete control of ultrafast polarization dynamics at femtosecond time scales, significantly extending the capabilities of X-ray spectroscopy and coherent imaging [39]. Likewise, attosecond pulse shaping using seeded free-electron lasers has demonstrated unprecedented control over extreme-ultraviolet pulse generation, opening new possibilities for ultrafast spectroscopy with attosecond temporal resolution [40].

The development of pulse-shaping methods is accompanied by significant advances in diagnostic and computational technologies. Accurate measurements of plasma dynamics under irradiation with temporally shaped femtosecond pulses make it possible to identify the role of transient material states and improve models of laser–material interactions. For example, considering electron–exciton processes during fused silica processing improved the accuracy of ablation morphology prediction, as confirmed by the comparison of simulated and experimental crater profiles (Figure 3) [41]. Numerical modeling of non-linear beam propagation in air further enables quantitative prediction of laser ablation characteristics by linking pulse evolution with the formation of material modifications [42].

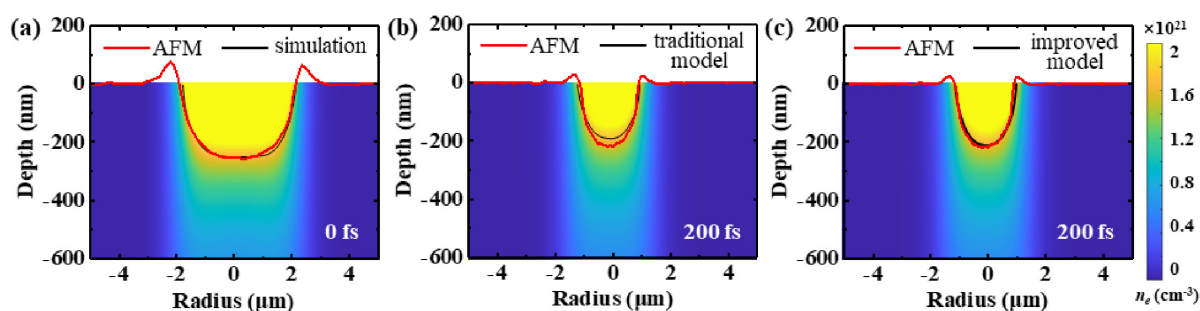


Figure 3. Experimental and simulated ablation crater profiles at pulse delays of (a) 0 fs and (b,c) 200 fs using conventional and improved models, respectively. Red lines: atomic force microscopy (AFM) measurements; black lines: numerical simulations [41].

Recent studies also demonstrate that adaptive pulse shaping can directly enhance application performance. For example, adaptive optimization of femtosecond pulse profiles significantly increases emission efficiency in volumetric displays through controlled excitation of individual voxels [43]. Furthermore, time-varying holographic optical fields generated using meta-holographic approaches represent a new generation of programmable ultrafast light sources capable of dynamic control over both spatial and temporal field distributions [44]. Consequently, different pulse-shaping approaches represent complementary solutions, each offering a different balance between controllability, efficiency, complexity, and application requirements.

Overall, recent developments indicate that femtosecond pulse shaping is evolving from a specialized coherent-control technique into a versatile approach for engineering ultrafast optical fields. The combination of programmable temporal modulation, adaptive optimization, metasurface photonics, artificial intelligence, and advanced diagnostics provides unprecedented flexibility in controlling laser–matter interactions. These advances establish the physical foundation for comprehensive optical field engineering, in which temporal, spatial, and spatiotemporal degrees of freedom are jointly exploited to achieve improved control of laser–matter interactions. Such integrated approaches provide the

basis for advanced beam-shaping architectures and adaptive optical systems enabling high-precision and high-throughput ultrafast laser micro- and nanofabrication.

3. Beam Shaping and Optical Field Engineering

Spatial beam shaping represents an important component of optical field engineering for ultrafast laser micro- and nanoprocessing. Unlike temporal pulse shaping, which modifies the temporal and spectral characteristics of femtosecond pulses, beam shaping directly controls the spatial intensity, phase, and polarization distribution of the optical field in the processing plane. This enables parallelization of laser–matter interaction, improvement of energy deposition uniformity, and extension of achievable fabrication geometries from simple scanning-based patterns to complex multi-focal and volumetric architectures.

An important foundation of modern beam shaping approaches lies in the development of structured illumination strategies and precise control of laser energy deposition. Early studies demonstrated that controlled manipulation of laser polarization and irradiation conditions enables deterministic tailoring of laser-induced surface morphologies and improves control over nanoscale structures [45]. These concepts were further reinforced by systematic studies of high-precision laser beam shaping, which established a direct relationship between engineered intensity distributions and deterministic control of ablation morphology [46]. In addition, comprehensive theoretical frameworks for spatially tailored ultrashort pulse delivery have clarified the critical role of optical system design in enabling controlled energy deposition in both lateral and axial dimensions [47].

In parallel, the exploitation of structured beam propagation in bulk and transparent media enabled early demonstrations of volumetric laser writing based on filamentation and light-sheet configurations, extending laser processing capabilities beyond surface-limited regimes and allowing the formation of periodic diffractive structures in three dimensions [48]. Concurrently, maskless lithography and interference-based exposure techniques provided scalable routes for large-area fabrication of complex micro- and nanostructures, including three-dimensional optical elements and light-guiding architectures [49]. More recent studies and reviews further highlight that phase-holographically controlled femtosecond laser processing enables deterministic fabrication of functional micro- and nanostructures across multiple length scales, thereby bridging fundamental beam physics with application-driven manufacturing strategies [50].

Modern approaches to spatial beam shaping for ultrafast laser processing are discussed in Ref. [51], with particular emphasis on dynamic wavefront manipulation to achieve high precision while maintaining energy efficiency. Various hardware solutions are employed to realize spatial intensity redistribution in the focal plane, including spatial light modulators (SLMs), deformable mirrors (DMs), acousto-optic deflectors, multi-plane light conversion (MPLC) systems, and the generalized phase contrast (GPC) method. Their overall classification is summarized in Figure 4. These architectures differ in their degrees of programmability, optical efficiency, response speed, and implementation complexity, making their suitability dependent on the requirements of a particular laser-processing application.

A key direction in this field is the development of programmable spatial modulation architectures based on spatial light modulators (SLMs). These devices allow dynamic control of phase and amplitude, enabling the generation of arbitrary intensity distributions and holographically reconstructed focal fields. Modern implementations increasingly exploit machine-learning-inspired concepts, such as diffractive neural networks, to optimize beam profiles for specific fabrication tasks, providing additional opportunities for improving shaping fidelity and system adaptability [52]. Complementary approaches based on non-linear phase modulation further extend the flexibility of SLM-based systems, enabling advanced control over femtosecond beam profiles for complex processing scenarios [53]. Be-

yond conventional holographic beam generation, considerable effort has also been devoted to improving the robustness and efficiency of SLM-assisted ultrafast laser processing.

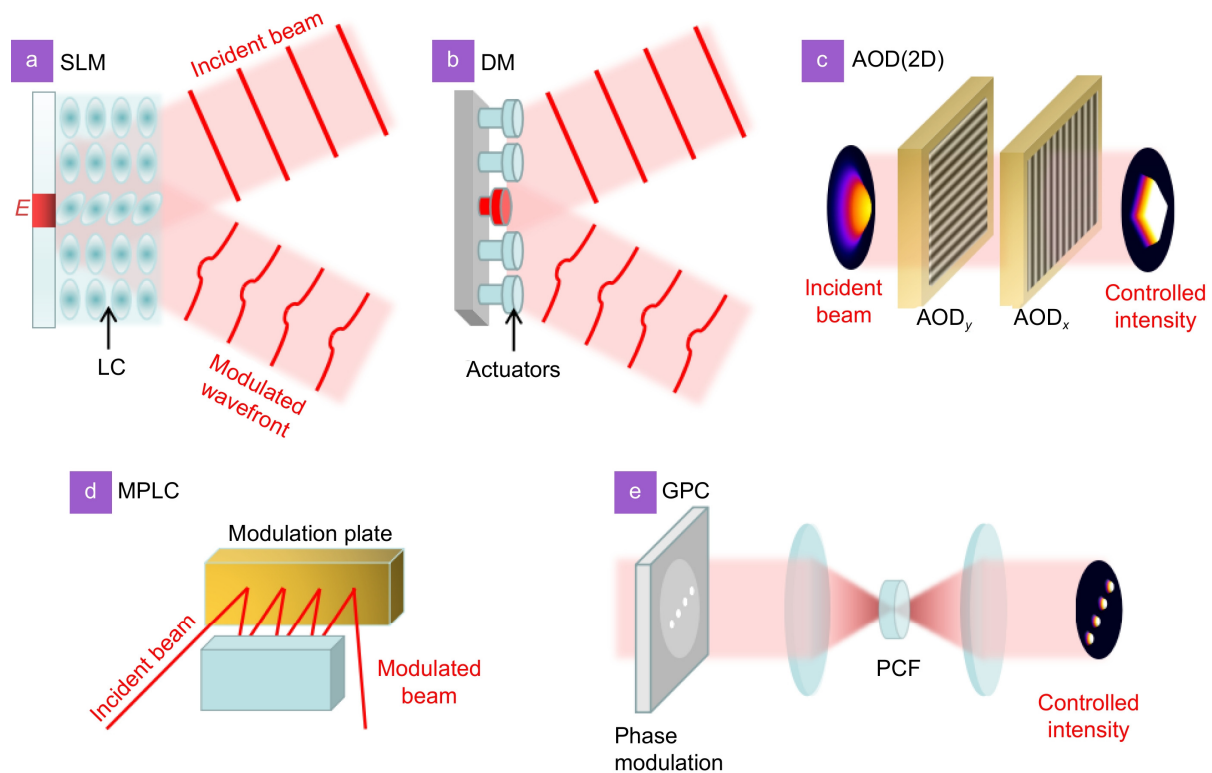


Figure 4. Classification of dynamic wavefront modulation approaches for spatial beam shaping. (a) Liquid crystal spatial light modulators (SLMs) with electrical control. (b) Deformable mirrors (DMs) with mechanical actuators. (c) Acousto-optic deflectors (AODs) using acoustic waves in a crystal for light diffraction. (d) Multi-plane light conversion (MPLC) systems for sequential mode transformation. (e) Generalized phase contrast (GPC), which converts phase modulation into intensity contrast using a phase contrast filter (PCF) [51].

Multi-imaging beam shaping has been proposed to increase processing throughput while preserving beam quality during parallel fabrication [54]. Power-handling capabilities of SLM systems have also been investigated for laser-induced periodic surface structuring (LIPSS), demonstrating that programmable beam shaping can be implemented even for millijoule-level femtosecond pulses without compromising pattern uniformity [55]. Phase-controlled wavefront engineering has furthermore been employed to overcome diffraction-limited focusing in ultrafast laser processing, enabling tighter energy localization than achievable with conventional focusing optics [56]. In parallel with these developments, alternative beam-shaping strategies based on nonlinear optical media have also emerged. In particular, nonlinear beam shaping in lithium niobate photonic structures has demonstrated complex spatiotemporal field manipulation enabled by engineered nonlinear interactions, providing an alternative route to programmable light control in volumetric media [57].

Complementary to programmable beam-shaping approaches, static optical architectures provide an alternative strategy for generating tailored focal intensity distributions. Refractive freeform optics and diffractive optical elements (DOEs) enable efficient transformation of Gaussian laser beams into process-adapted intensity profiles without requiring active modulation during operation. Such approaches are particularly attractive for industrial ultrafast laser systems, where high optical efficiency, robustness, and reproducibility are required. Computationally designed refractive beam shapers have demonstrated the conversion of Gaussian femtosecond laser beams into squared top-hat intensity distribu-

tions, showing good agreement between simulated and experimentally measured focal intensity profiles, as illustrated in Figure 5 [58].

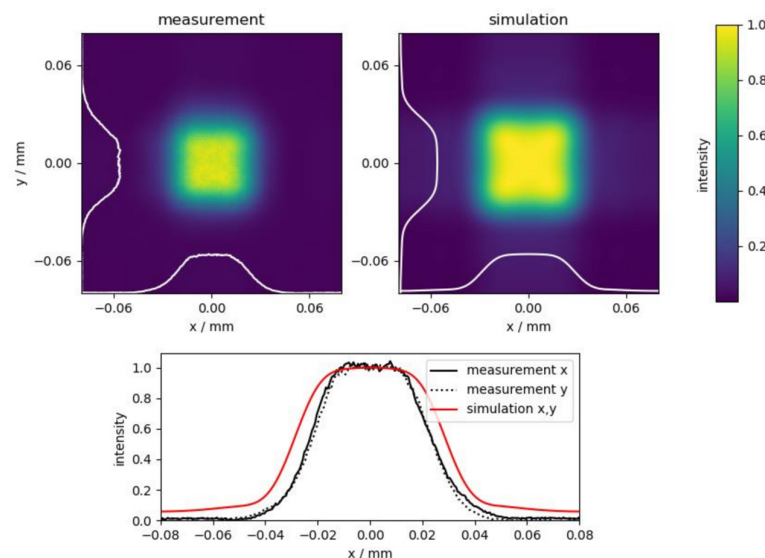


Figure 5. Color maps and cross-sections of the squared focal top-hat intensity distribution near the focal plane ($\lambda = 1064$ nm, $f = 300$ mm), normalized to maximum intensity for comparison between measurement and simulation [58].

DOEs further extend these capabilities by enabling phase-based wavefront engineering for flat-top beam shaping and controlled redistribution of laser energy. Recent studies demonstrate the practical importance of DOE-based optical field redistribution for industrial ultrafast laser processing. Long et al. employed a DOE to transform a Gaussian femtosecond laser beam into a square-shaped flat-top focus for centimeter-scale micro-machining of single-crystal 4H-SiC substrates. The homogenized intensity distribution improved ablation uniformity, reduced material redeposition, and enabled high-quality large-area processing [59]. Beyond intensity homogenization, DOE-based beam splitting provides an effective strategy for increasing processing throughput. A multibeam drilling system based on a fused-silica DOE was demonstrated for the simultaneous fabrication of multiple microholes in titanium sheets. Combined with spatial filtering of unwanted diffraction orders and appropriate optical power management, the system enabled reliable operation under kilowatt-class average laser powers [60].

Compared with programmable beam-shaping systems, static optical architectures generally provide higher optical efficiency and robustness, whereas programmable approaches offer greater flexibility for adapting optical fields to different processing conditions. However, the fixed optical response of conventional DOEs limits their adaptability when processing parameters or target geometries must be modified dynamically. This limitation has motivated the integration of diffractive concepts with programmable spatial light modulators, enabling adaptive beam shaping through computer-generated holography. In this approach, the phase distribution of the diffractive element is generated and updated electronically, allowing rapid modification of the resulting intensity pattern without replacing physical optics. Ref. [61] demonstrated such a programmable diffractive beam-shaping strategy for femtosecond laser sulfur hyperdoping of silicon, where an LCoS-SLM generated a computer-generated hologram that transformed the Gaussian beam into a line-shaped intensity distribution.

Another widely used class of programmable beam-shaping devices is represented by digital micromirror devices (DMDs), which provide high-speed binary amplitude modulation of optical fields. Their rapid switching capability enables dynamic reconfiguration of

structured illumination, supporting high-speed maskless lithography, beam patterning, and other large-area parallel laser processing strategies. Recent developments include scalable maskless lithography for three-dimensional microstructure fabrication, demonstrating the applicability of DMD-based projection systems to industrial laser processing [62]. Detailed investigations of DMD optical performance have improved their integration into ultrafast laser systems, particularly for femtosecond laser applications requiring precise synchronization and efficient light utilization [63,64]. Vector-field approaches based on DMD-assisted architectures further extend optical field engineering toward polarization-resolved intensity distributions, enabling additional control of laser-processing parameters [65].

To achieve sub-diffraction patterning in projection lithography, DMD-based multiple-exposure strategies have been developed, exploiting the nonlinear response of photoresists under sequentially shifted mask projections. These approaches enable feature separation below the classical diffraction limit by suppressing overlap of optical intensity distributions, as illustrated in Figure 6 [66]. Femtosecond laser fabrication with wavefront control enables precise micro- and nanostructuring via localized energy deposition [67], while phase-controlled SLM-based light-field lithography ensures accurate reconstruction of volumetric structures through joint amplitude–phase field matching [68]. Together, these approaches demonstrate the combined role of nonlinear exposure and wavefront engineering in extending lithographic resolution limits.

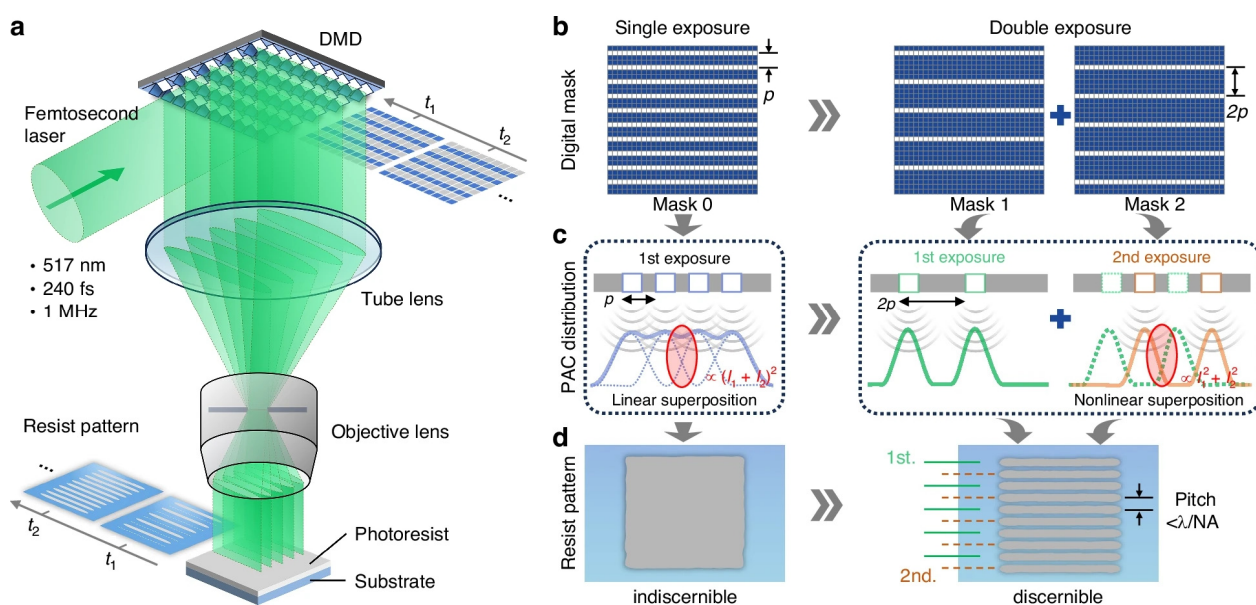


Figure 6. DMD-based multiple-exposure projection lithography: (a) experimental setup; (b) comparison of single- and double-exposure mask layouts; (c) comparison of photoactive compound (PAC) distributions for linear and nonlinear exposure; (d) predicted and experimental photoresist patterns demonstrating sub-diffraction patterning [66].

In DMD-based projection systems, efficient laser energy utilization is governed by the diffraction characteristics of the micromirror array, which acts as a two-dimensional diffraction grating that redistributes the incident radiation into discrete diffraction orders. By optimizing the illumination geometry, particularly the incident angle and orientation of the laser beam relative to the DMD pixel structure, the energy concentration in the selected diffraction order can be increased, improving the overall efficiency of projection lithography systems. The operating principles of DMD diffraction and different illumination regimes are summarized in Figure 7 [69]. Such optimization approaches are important for maintaining high process efficiency in large-area parallel fabrication.

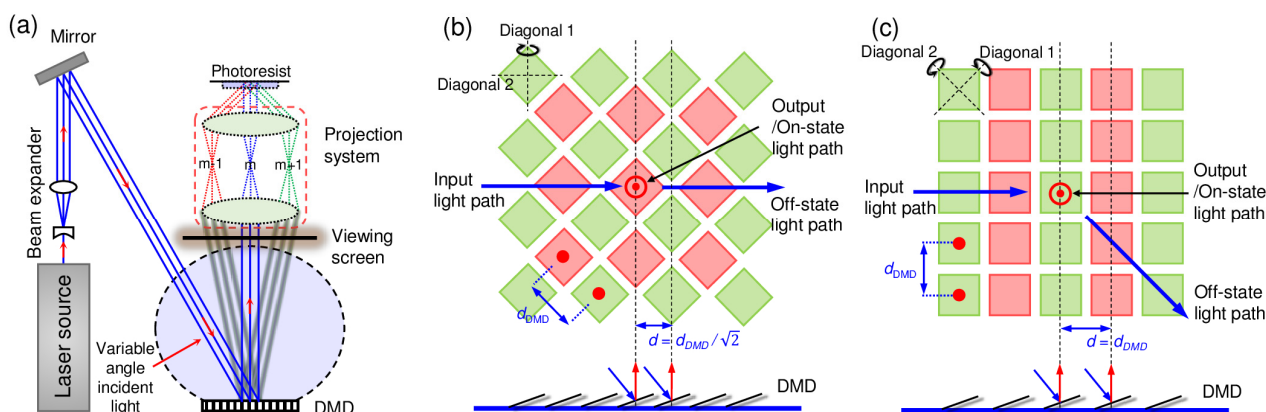


Figure 7. Diffraction model and operating regimes of a DMD for projection lithography. (a) Schematic of a DMD-based system and formation of diffraction orders $m-1$, m , and $m+1$. (b) Conventional operation mode with diagonal illumination relative to the micromirror array. (c) Tilt-and-Rotate Pixel (TRP) mode with edge-direction illumination. Here, d denotes the equivalent grating period, while d_{DMD} corresponds to the physical pixel pitch of the DMD [69].

The increasing number of controllable optical-field degrees of freedom has driven the development of increasingly sophisticated optical architectures, enabling advanced control of light–matter interactions and multifunctional laser processing. Figure 8 summarizes this hierarchical evolution, from spatial amplitude and phase control toward vectorial, temporal, and spatiotemporal field engineering, emphasizing the transition from single-domain field manipulation to integrated multi-domain optical control.

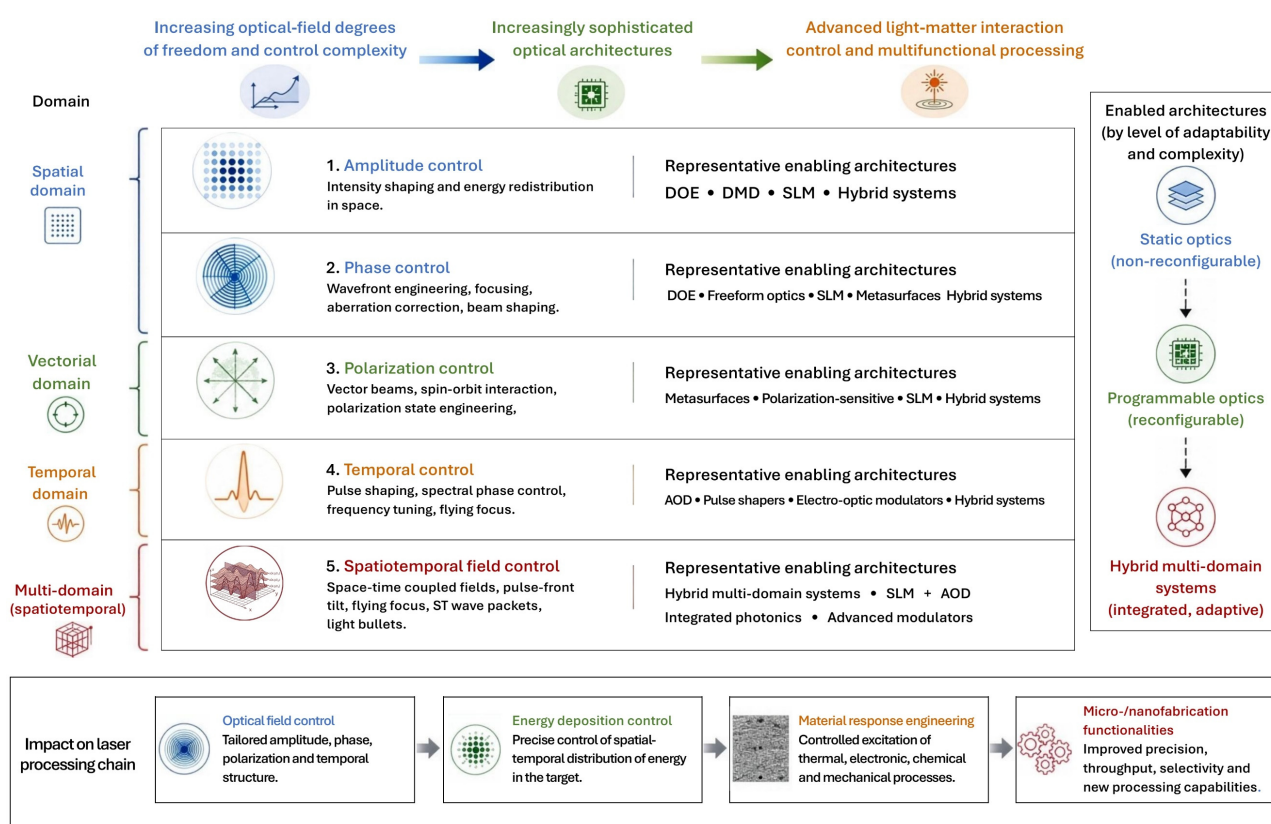


Figure 8. Conceptual framework of optical-field engineering, illustrating the evolution from spatial amplitude and phase control toward vectorial, temporal, and spatiotemporal field manipulation enabled by increasingly sophisticated optical architectures.

Overall, modern beam-shaping architectures represent a transition from passive optical transformation toward programmable and hybrid control of ultrafast optical fields. Static refractive and diffractive elements provide high efficiency, robustness, and reproducibility for industrial processing, whereas SLM- and DMD-based systems enable adaptive generation of complex intensity distributions. Together, these approaches demonstrate that modern optical field engineering relies on complementary optical architectures, with the choice of a particular solution depending on the balance between efficiency, flexibility, robustness, and process-specific requirements.

4. Applications of Optical Field Engineering in Ultrafast Laser Processing

Recent applications of optical field engineering demonstrate how controlled manipulation of spatial and spatiotemporal laser characteristics can influence processing efficiency, structural fidelity, and scalability in ultrafast manufacturing. Among the spatial control strategies within optical field engineering, hybrid architectures combining static optical elements with programmable SLMs have emerged as promising solutions for industrial laser systems. By combining the efficiency of refractive optics with the adaptability of dynamic phase modulation, such architectures provide stable quasi-flat-top intensity distributions for high-quality material processing [70]. Holographic field synthesis represents another important pathway in optical field engineering, where phase-only modulation enables the generation of programmable multi-focus distributions for parallelized fabrication. Digital holography-based approaches provide deterministic control of laser focus positioning and energy deposition, enabling parallel three-dimensional nanofabrication with up to 2000 individually programmable foci. Such systems have demonstrated nanoscale feature formation (down to 90 nm) and volumetric fabrication rates on the order of 10^6 voxels s^{-1} , highlighting the potential of holographic field synthesis for high-throughput ultrafast manufacturing [71]. The principle of a multi-focus two-photon lithography system based on digital holography is illustrated in Figure 9, showing the optical configuration, parallel writing strategy, and representative fabricated structures.

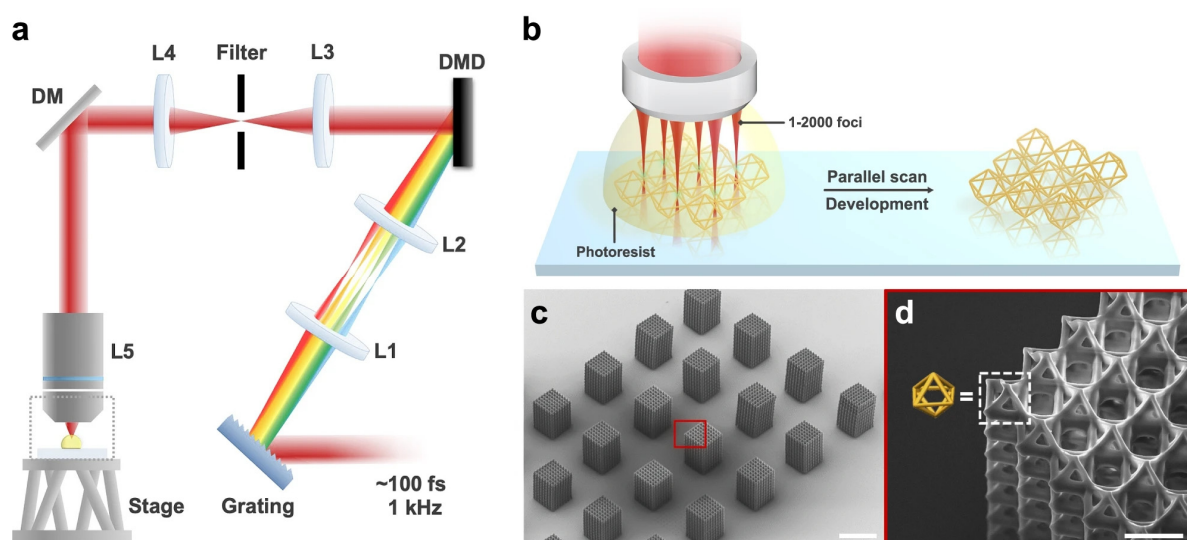


Figure 9. Multi-focus two-photon lithography based on digital holography for parallel three-dimensional nanofabrication. (a) Optical configuration of the holographic fabrication system, including lenses (L1–L5), a digital micromirror device (DMD), and a dichroic mirror (DM). (b) Principle of parallel writing using a multi-focus distribution. (c,d) Representative fabricated lattice structures [71].

Metalens-based optical architectures further extend the capabilities of parallel two-photon lithography by replacing conventional focusing optics with densely integrated

arrays of micro-optical elements [72,73]. Hybrid systems combining static metalens arrays with programmable spatial light modulation have demonstrated massively parallel laser fabrication using more than 120,000 individually controlled focal spots and processing rates exceeding 10^8 voxels s^{-1} while maintaining independent grayscale linewidth control for each focus. Such architectures provide a potential approach for reducing limitations associated with the field of view and image-stitching requirements of conventional multifocal lithography, demonstrating that metasurfaces can serve not only as pulse-shaping elements but also as focusing components for large-area massively parallel laser processing [74].

Beyond externally implemented spatial modulation systems, recent developments focus on integrated optical approaches in which ultrafast lasers are used to directly fabricate optical elements for wavefront and polarization control in transparent materials. Femtosecond laser writing enables geometric phase and polarization engineering in silica glass, producing ultralow-loss optical components for advanced manipulation of optical fields [75]. Such strategies extend optical field engineering beyond external modulation toward the fabrication of integrated optical components with tailored wavefront and polarization functionality. Advanced field-control concepts also include structured light approaches for tailoring energy deposition in spatial and temporal domains. Structured illumination provides additional control over energy deposition and feature formation in ultrafast laser micro- and nanoprocessing by enabling customized focus distributions and controlled energy deposition for advanced material processing [76]. The scalability of this concept has been demonstrated by combining DOE-based beam splitting with synchronized galvanometric scanning, enabling high-rate parallel processing over large areas [77]. A diffractive optical element enabled large-area LIPSS fabrication by generating 2601 parallel processing spots, achieving a reported throughput of $1910 \text{ cm}^2 \text{ min}^{-1}$ while the processing system incorporated infrared monitoring of heat accumulation during laser irradiation [78].

Diffractive beam engineering also enables the fabrication of application-specific functional surfaces. Ultrashort pulsed direct laser interference patterning (USP-DLIP), implemented using DOE-generated coherent interference fields, has been employed to fabricate periodic line-like structures with a $3 \text{ }\mu\text{m}$ period on brass substrates using 100 fs laser pulses. The resulting surface topography was shown to influence bacteria–substrate interactions, demonstrating the potential of optical-field engineering for fabricating biofunctional surface structures [79]. Complementary approaches exploit dynamic control of laser energy deposition during scanning. Feature-synchronous energy coupling enables adaptation of the laser–material interaction to transient process conditions, reducing thermal accumulation and improving fabrication quality [80].

Complementary approaches to SLM- and DMD-based systems include acousto-optic modulation and adaptive wavefront engineering, providing additional degrees of freedom for ultrafast optical field manipulation. Acousto-optic beam shaping enables dynamic generation of complex three-dimensional intensity distributions, including hollow cylindrical (bottle-beam) fields with axial-to-transverse aspect ratios of approximately 9:1 and sub-100 μs tuning capability, demonstrating the flexibility of acoustic-wave-driven diffraction for reconfigurable optical field control [81]. In parallel, adaptive wavefront control techniques have been employed to steer femtosecond filamentation within transparent materials, enabling deterministic localization and tailoring of energy deposition during volumetric structuring [82]. These adaptive beam-shaping strategies have also been translated to the fabrication of buried microchannels in polymers, where SLM-based correction of spherical aberration and programmable beam shaping enable precise three-dimensional energy delivery and controlled internal modification of transparent materials [83].

From an application perspective, optical field engineering has been demonstrated across a broad range of ultrafast laser manufacturing processes, where controlled manipu-

lation of spatial and temporal energy distributions enables improved precision, scalability, and process functionality. Multi-focus and multi-beam lithography approaches allow parallel fabrication of photonic structures with nanoscale resolution, increasing processing efficiency while maintaining high structural fidelity [84]. Similar concepts have been extended to the fabrication of micro-optical elements, where engineered ultrafast laser intensity distributions provide additional control over material modification and enable the formation of functional optical components [85]. Furthermore, structured beam approaches have been investigated for ultrafast laser welding of transparent materials, demonstrating that tailored energy deposition profiles can improve joining quality by reducing defects associated with conventional Gaussian irradiation [86].

Beyond individual fabrication processes, optical field engineering provides new opportunities for controlling material response through spatially and temporally tailored laser–matter interaction. Spatially shaped femtosecond laser beams have been employed to generate anisotropic microstructures by modifying melt dynamics and local energy deposition conditions. In one example, variations in scanning speed from 300 to 1000 $\mu\text{m/s}$ were used to regulate the transition between sharp anisotropic features and continuous groove-like morphologies, demonstrating the role of pulse accumulation and thermal feedback in structure formation [87]. Beam shaping has also been applied to infrared optical materials, where conversion of Gaussian beams into line-shaped profiles using cylindrical optics enabled efficient fabrication of antireflective structures. A line-beam configuration expanded the processed width from micrometer-scale Gaussian spots to several millimeters, providing an approximately 393-fold increase in the single-scan processed area compared with conventional Gaussian-beam irradiation. Using a 500 mW femtosecond laser at a scanning speed of 1.0 mm/s, a $1 \times 1 \text{ cm}^2$ ZnS antireflective surface was fabricated within 21 s, resulting in improved infrared transmission [88].

The flexibility of optical field synthesis is further demonstrated by holographic and programmable beam-generation methods. SLM-based approaches combined with computer-generated holograms (CGHs) enable the fabrication of complex terahertz metasurfaces by generating spatially controlled Bessel-like beam profiles. Such methods allow precise printing of subwavelength resonant elements with different geometrical parameters and provide a versatile route for manufacturing non-periodic functional optical architectures [89]. Similarly, customized beam profiles have been introduced into femtosecond laser welding of polymer microfluidic chips, where optimization of the intensity distribution suppresses burning and bubble formation observed with Gaussian beams. The application of shaped beams increased the welding speed compared with conventional processing, enabling fabrication of $45 \times 7.5 \text{ mm}^2$ microfluidic chips in less than 20 s [90].

For high-power ultrashort-pulse laser systems, optical field engineering is increasingly combined with programmable modulation and parallel processing strategies. Spatial light modulators provide flexible phase control for beam shaping and splitting, enabling transformation of Gaussian beams into predefined intensity distributions. Using SLM-based phase masks generated by iterative algorithms such as the Gerchberg–Saxton method, high-power femtosecond beams can be divided into multiple processing channels. Demonstrated systems operated with USP lasers up to 100 W output power and pulse energies up to 500 μJ , providing a basis for parallelized micromachining approaches [91]. The principle of programmable beam shaping is illustrated in Figure 10, showing the conversion of an incident Gaussian beam into tailored intensity profiles.

Further integration of optical field control with programmable scanning architectures enables more flexible and efficient strategies for high-throughput laser fabrication. Conventional SLM-based multifocus systems are limited by the relatively slow modulation rate of spatial phase patterns, which restricts the generation of dynamic and non-periodic pro-

cessing trajectories. DMD-based approaches offer an alternative by rapidly controlling the number and spatial arrangement of active laser foci, enabling adaptive energy distribution during scanning. By dynamically switching up to 36 processing foci while maintaining high intensity uniformity ($\approx 98\%$), such systems significantly enhance fabrication efficiency through adaptive control of energy deposition and non-periodic scanning trajectories [92].

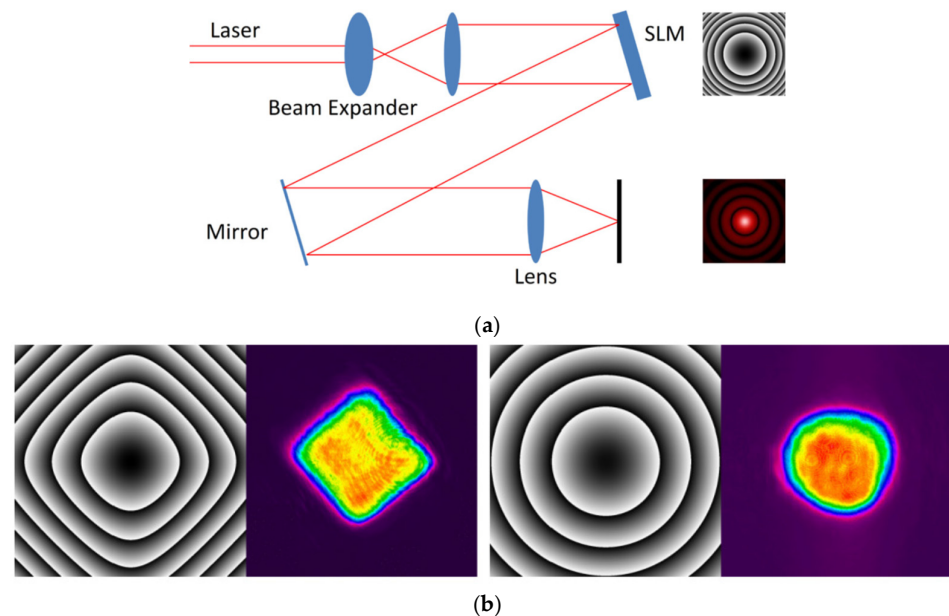


Figure 10. Programmable laser beam shaping for high-power ultrashort-pulse laser systems. (a) Optical scheme for SLM-based focus shaping; (b) phase masks and experimentally generated flat-top intensity distributions with a characteristic diameter of approximately 300 μm [91].

A particularly important application direction is the use of engineered optical fields for functional surface modification. Temporal and spatial shaping of femtosecond laser irradiation enables fabrication of bioinspired subwavelength structures with controlled morphology and surface functionality. Double-pulse Bessel beam processing was used to fabricate antireflective inverted-cone arrays on ZnS substrates, where pulse energy and delay time provided control over structure depth and aspect ratio. Using a 216 fs, 1030 nm femtosecond laser operating at 10 kHz, the process enabled fabrication of subwavelength inverted-cone arrays with controlled dimensions (approximately 2.4 μm diameter and 0.92 μm depth), providing enhanced optical transmission and improved surface durability through tailored energy deposition [93].

Engineered ultrafast laser fields also expand the processing capabilities for ultrahard materials such as diamond. Femtosecond laser direct writing with a 400 nm laser source enabled fabrication of subwavelength surface structures with periods of approximately 100 nm. By controlling laser polarization and scanning trajectories, complex micro–nano patterns were produced on diamond surfaces, demonstrating potential for friction-reducing coatings, nanoimprint templates, Raman-enhanced substrates, and optical structures [94].

Application-driven studies further demonstrate the transition from optical field control toward functional device fabrication. Spatial–temporal shaping of femtosecond laser irradiation using double-pulse Bessel beams enabled the fabrication of gradient microcolumn arrays for triboelectric pressure sensors. By controlling the laser-induced modification depth through Bessel beam parameters and subsequent processing steps, gradient structures with a height difference of 2 μm were produced, enabling improved sensor linearity and functional performance [95].

Overall, the combination of programmable spatial modulation, holographic beam synthesis, structured light generation, and hybrid optical architectures provides a diverse toolbox for ultrafast laser micro- and nanofabrication. These approaches enable scalable high-throughput processing while preserving submicrometer precision and demonstrate a transition from isolated beam manipulation toward integrated control of spatial, temporal, and spatiotemporal laser-field characteristics. Such developments contribute to emerging adaptive manufacturing concepts based on integrated engineering of ultrafast optical fields.

5. Optical Architectures for Spatial and Spatiotemporal Control of Ultrashort Laser Pulses

Spatial and spatiotemporal engineering of ultrashort laser pulses has evolved from passive optical architectures toward programmable and hybrid systems capable of tailoring intensity distributions, phase, polarization, and temporal evolution of ultrafast optical fields. In the context of laser micro- and nanofabrication, this evolution enables a transition from conventional serial scanning strategies toward parallel, adaptive, and multidimensional processing regimes, improving processing efficiency, structural control, and scalability while expanding the range of achievable structures [96]. Figure 11 qualitatively compares the principal optical architectures used for ultrafast optical field engineering, illustrating the transition from passive static optics toward programmable and hybrid multi-domain systems. Hybrid architectures combine the high efficiency of static optical elements with the adaptability of programmable platforms, although their practical implementation requires careful optimization of system complexity, alignment stability, and computational efficiency.

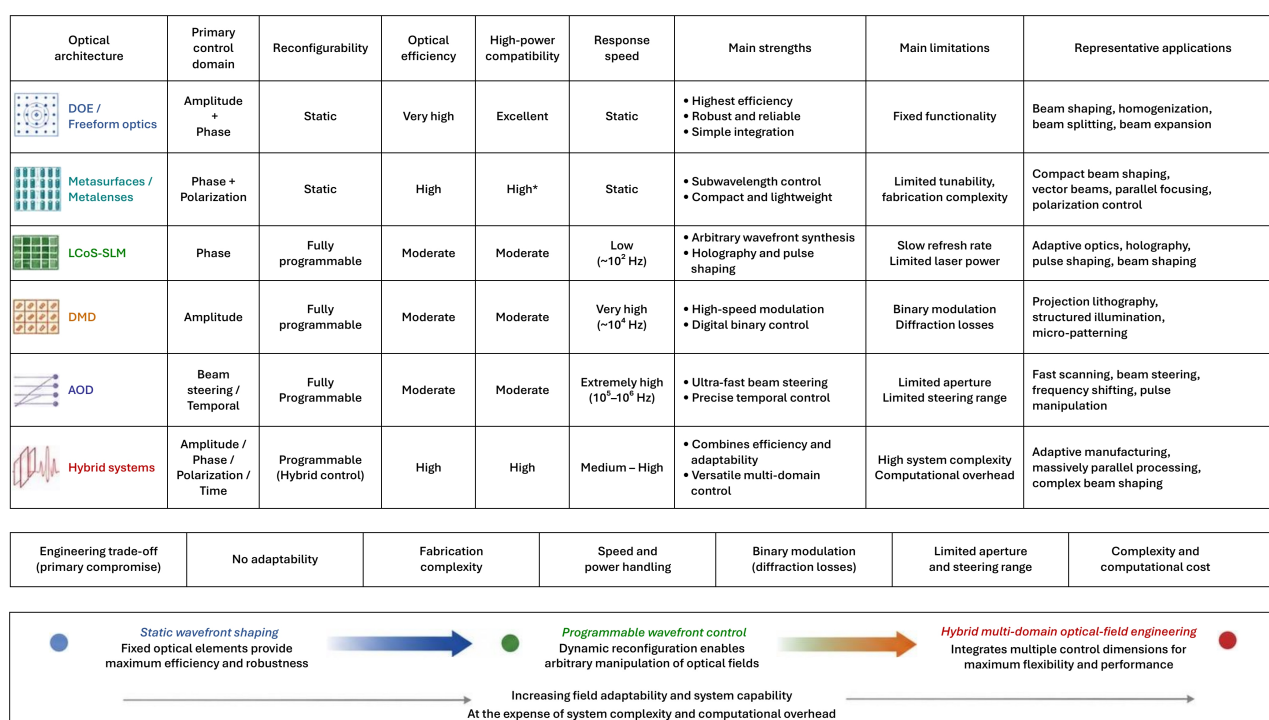


Figure 11. Qualitative comparison of major optical architectures used for ultrafast optical field engineering, highlighting control domains, adaptability, optical efficiency, laser compatibility, response characteristics, and representative applications. * High-power compatibility for metasurfaces is material- and design-dependent.

Static and semi-static architectures based on diffractive and refractive optical elements, including DOEs and freeform optics, provide high optical efficiency, excellent reproducibil-

ity, and compatibility with high-energy ultrashort laser systems, making them attractive for high-throughput industrial laser processing [97]. The generation of tailored intensity distributions, such as flat-top profiles, improves energy deposition uniformity and processing quality compared with conventional Gaussian beams [98]. Highly efficient beam homogenization strategies have recently been demonstrated for high-energy femtosecond laser systems [99]. Advances in computational design and fabrication workflows for freeform and diffractive optical elements have further improved the manufacturability, scalability, and performance of static field-transformation approaches [100]. Differentiable optimization methods enable smoother phase profiles with reduced parasitic scattering and improved optical performance [101], while femtosecond laser inscription provides a flexible route for rapid fabrication of customized diffractive structures [102].

The principal limitation of static architectures is their fixed optical response, which prevents adaptation during processing. Consequently, these systems are well suited for stable, high-throughput manufacturing but remain less flexible than programmable solutions for applications requiring real-time modification of the generated intensity distribution [103]. Dynamic architectures rely on programmable optical modulators and beam-control devices, including LCoS-SLMs, DMDs, AODs, and MEMS-based systems. Their key advantage is programmable control of optical phase, amplitude, or beam trajectory, enabling arbitrary intensity distributions, multi-focus beam generation, adaptive field modification, and beam splitting within a single optical configuration [104]. Recent experimental studies have demonstrated the application of structured-light-based femtosecond laser patterning of functional materials, such as GST thin films, highlighting the potential of programmable beam shaping for advanced micro/nanofabrication processes [105].

The increased flexibility of programmable systems is accompanied by several practical limitations. For LCoS-SLM devices, diffraction efficiency, spatial resolution, refresh rate, and damage threshold remain critical parameters restricting their application in high-power femtosecond laser systems. Recent studies have demonstrated that intense femtosecond irradiation can induce optical damage in SLM devices, defining important operational limits for high-energy femtosecond laser applications [106]. DMD-based systems provide extremely high switching speeds but exhibit reduced optical efficiency due to binary amplitude modulation [107]. AOD-based architectures offer ultra-fast beam steering but at the expense of reduced spatial flexibility and increased optical complexity [108].

Holographic field synthesis represents a versatile approach for generating complex optical distributions. Digital holography combined with computational algorithms enables the formation of three-dimensional intensity landscapes with precise control over multiple focal positions, which is particularly important for parallel nanofabrication [109]. In two-photon lithography systems, such approaches enable high-throughput parallel structuring with submicrometer resolution [110]. However, computational complexity and speckle noise remain key limitations, motivating the development of inverse design strategies and differentiable optimization methods for optical systems [111,112]. Further development directions include hybrid architectures combining static DOEs, programmable SLMs, and digital holographic approaches. These systems distribute optical power among multiple elements, improve energy utilization, reduce parasitic diffraction effects, and maintain high adaptability of the generated optical fields [113].

While most practical implementations currently focus on spatial field control, emerging approaches increasingly extend optical-field engineering toward coupled spatial-temporal manipulation. An important extension of these concepts is the spatiotemporal control of ultrashort laser fields, where spatial modulation is coupled with nonlinear laser-matter interaction dynamics, resulting in complex field evolution and structured energy deposition regimes [114]. Another promising direction involves integrated optical elements and functional materials

for optical-field generation. Direct laser writing of optical elements inside transparent media enables three-dimensional photonic structures with tailored phase and polarization responses, forming the basis for integrated optical control systems without external modulators [115]. Similarly, spatial modulation of laser fields can be employed for controlled nanofabrication in silicon, enabling localized material modification and controlled structural transformations [116]. Furthermore, femtosecond laser nanolithography in crystalline materials enables the formation of complex three-dimensional structures with high precision and orientation control, which is particularly relevant for integrated photonic devices [117].

Comparison of available architectures indicates that static optical elements generally provide high optical efficiency and operational robustness, whereas programmable systems offer enhanced adaptability for dynamic control of laser fields. Holographic and hybrid approaches combine these advantages by providing a balance between field reconfigurability, processing throughput, and optical performance. Consequently, the optimal strategy for ultrafast optical field engineering is determined by the balance between laser power, processing speed, reconstruction accuracy, and the required degree of spatial and spatiotemporal control [96,103]. To summarize the main characteristics of these architectures, a comparative overview of their modulation principles, efficiency, response speed, laser compatibility, and spatial control capability is provided in Table 1.

Table 1. Comparison of major optical architectures for spatial and spatiotemporal control of ultrashort laser fields.

Architecture (Representative References)	Optical Efficiency/Diffraction Efficiency	Refresh Rate/Response	Laser Compatibility	Modulation Type	Spatial Resolution
LCoS-SLM [17,20,50,55,80,91,104,106]	High (~60–90%, depending on configuration)	Low (60–240 Hz; up to ~1–2 kHz in specialized systems)	Moderate; limited by liquid-crystal damage threshold and thermal effects	Continuous phase modulation (8–16 bit)	Very high (megapixel; ~4–8 μm pixel pitch)
DMD [24,62–65,69,92]	Moderate for holography; higher in blaze configurations	High (up to ~20–32 kHz)	Moderate; limited by micromirror coating and thermal load	Binary amplitude; holographic phase modulation possible	High (megapixel; ~7–13 μm pixel pitch)
AOD/AOM [81]	Typically tens of percent to >80%, depending on configuration	Very high (hundreds of kHz–MHz)	Crystal-limited	Dynamic amplitude or phase modulation	Limited by aperture and bandwidth
DOE [58,60,61,76]	Very high (often >90% for optimized designs)	Static	Excellent for high-power operation	Static phase modulation	High but fixed after fabrication
Freeform optics [58,99–101]	Very high	Static	Excellent stability and power compatibility	Static refractive/diffractive shaping	High (continuous surface profile)
Hybrid adaptive systems [51,70,80,91,113]	Medium to high (architecture dependent)	Dynamic	High	Combined static + programmable modulation	High
Deformable mirrors (DM) [106,113]	High (reflective; typically >95%)	Hundreds of Hz–kHz	High (coating-dependent)	Continuous phase modulation	Moderate (limited by actuator number)
Metasurfaces/metalenses [32,33,44,74]	High (design-dependent; up to ~80%)	Static; dynamic control via SLM integration	Material/wavelength dependent; scalable fabrication	Wavefront control and high-NA focusing	Subwavelength resolution

Reported optical efficiency values depend strongly on the modulation scheme, phase pattern design, wavelength, polarization conditions, and optical configuration. Therefore, the values summarized in Table 1 should be regarded as representative ranges rather than intrinsic limits of each architecture. Emerging approaches, including multi-plane light conversion (MPLC), generalized phase contrast (GPC), and lithium-niobate spatial light modulators, provide additional opportunities for structured light generation and advanced wavefront control but are not included because of their comparatively limited use in ultrafast laser material processing.

While Table 1 compares the intrinsic characteristics of the major optical architectures, their practical significance is ultimately reflected in laser-processing performance. Representative application-oriented metrics, including processing rate, parallelization strategy, achievable resolution, and throughput improvement, are summarized in Table 2.

Table 2. Representative application-level performance metrics of optical-field engineering strategies for ultrafast laser micro- and nanofabrication.

Application Area (Representative References)	Representative Optical Architectures	Parallelization/Field Strategy	Typical Performance Indicators	Achievable Resolution	Processing Improvement/ Throughput Gain
3D micro-/nanofabrication (TPP, volumetric printing) [10,12,21,25,26,71,74,111]	DMD, LCoS-SLM, holographic beam shaping, light-sheet projection, metalens arrays	Multifocal/voxel parallelization; two-photon and volumetric printing	Up to 10^8 voxels s^{-1} ; parallel writing with $>10^5$ focal spots demonstrated	$\sim 20\text{--}200$ nm; sub-diffraction features	Higher throughput than single-focus TPP; reduced stitching constraints for large-area fabrication
Surface structuring and LIPSS fabrication [45,61,73,74,86,93]	SLM, DOE, cylindrical lenses, spatiotemporal beam shaping	Line-beam, multi-beam and patterned irradiation; temporal/polarization control	Processing rates up to ~ 2000 cm^2 min^{-1} ; large-area functional structuring demonstrated	Sub-100 nm periodic structures; LSFL/HSFL	Increased area coverage and reduced processing time, depending on beam-shaping strategy
Microdrilling and precision ablation [17,60,65,92]	DMD–galvo hybrid, DOE, SLM beam splitting	Multi-focus drilling; dynamic mask projection	Material removal rates up to 230 mm^3 min^{-1} ; simultaneous drilling with multiple spots	Submicrometer projection linewidths; μm -scale holes	Higher throughput than single-beam drilling through simultaneous multi-focus irradiation
Large-area functional surface modification [58,59,70,98,100]	DOE, freeform optics, hybrid beam-shaping systems	Flat-top and tailored intensity distributions; beam homogenization	Optical efficiency approaching 90%; uniform cm-scale processing	Transition zones < 10 μm ; nanoscale roughness control	Improved uniformity and scalability relative to Gaussian-beam processing
In-volume modification and transparent materials processing [47,82,83,96,112]	Adaptive SLM, 3D DOE splitters, Bessel beams, axicons	Multifocal depth-selective deposition; adaptive wavefront control	Extended-depth processing and controlled filament-assisted modification	Submicrometer internal structures; aspect ratios up to $\sim 700:1$	Reduced fabrication time and increased processing depth focused-beam processing
Photonic structures and optical component fabrication [44,50,84,89,109,110]	Holography, FrFT beam shaping, DNN-based beam shaping, freeform holograms	Programmable 3D field generation; wavelength-adaptive multi-beam writing	Parallel fabrication of waveguides, metasurfaces and micro-optical elements; diffraction efficiency $> 90\%$	$\sim 30\text{--}50$ nm (advanced lithography) to micrometer-scale structures	Greater fabrication flexibility and throughput than serial direct laser writing

As summarized in Table 2, the practical benefits of optical-field engineering depend strongly on the target application and the adopted beam-shaping strategy. The greatest improvements are typically achieved in inherently parallel processing schemes, whereas processes requiring high local fluence or deep volumetric modification remain limited by laser power, energy distribution, and the nonlinear response of the material.

Data-driven control approaches for spatiotemporal laser fields, including differentiable programming [118], provide additional possibilities for adaptive optimization of laser-field characteristics. The performance of ultrafast laser processing is ultimately limited not only by the optical architecture but also by the nonlinear response of the processed material. Increasing the number of simultaneously generated focal spots requires higher peak laser power, which limits the scalability of parallel processing. For surface microstructuring, maintaining an appropriate fluence window remains essential for achieving uniform and reproducible modification. Future advances will increasingly rely on the joint optimization of spatial, temporal, and polarization characteristics of ultrashort laser fields within a unified optical-field engineering framework, providing a foundation for predictive and adaptive control of laser–matter interactions.

6. Perspectives and Challenges in Optical Field Engineering for Ultrafast Laser Processing

The development of ultrafast optical field engineering has significantly expanded the capabilities for controlling laser-field characteristics across spatial, temporal, and spatiotemporal domains, enabling more precise energy deposition strategies and advanced micro- and nanofabrication approaches [1–3,20,51]. Further industrial adoption of engineered optical fields requires addressing several key challenges, including optical system stability, high-power operation, computational optimization, and process scalability. Future progress will depend on the integration of robust optical architectures, adaptive control strategies, and material-specific optimization of laser–matter interactions.

6.1. Industrial Implementation Challenges

A major challenge for industrial application of engineered optical fields is maintaining long-term system stability and processing reproducibility. Optical drift, mechanical vibrations, and calibration errors can modify the generated intensity distributions and reduce process consistency during extended operation. In programmable and hybrid systems, alignment tolerance of optical components, including SLMs and DOEs, together with beam-pointing stability, remains critical for maintaining accurate field reconstruction and energy delivery [51,55,108].

High-power operation introduces additional limitations associated with optical damage thresholds, efficiency losses, and thermal management. Although programmable beam-shaping approaches provide increased flexibility, their scalability is restricted by the power-handling capability of optical components and by energy losses associated with beam shaping and field reconstruction [55,69,106]. Furthermore, the final quality of laser-processed structures is strongly influenced by nonlinear laser–matter interaction mechanisms, including transient absorption, plasma formation, heat accumulation, and structural transformations within the material [42,114]. Therefore, industrial implementation requires simultaneous optimization of optical architecture, thermal effects, and material-specific processing conditions.

6.2. Computational and Adaptive Control

The increasing complexity of engineered optical fields requires advanced computational approaches for efficient design, optimization, and adaptive control. Recent devel-

opments in differentiable optimization, inverse design, and neural-network-based optical design have demonstrated new possibilities for generating complex intensity and phase distributions with improved reconstruction accuracy and reduced design time [52,100,101,111]. These approaches enable efficient exploration of large optical design spaces, where conventional analytical methods and experimental parameter scans become increasingly impractical. Consequently, computational optimization is becoming an essential component of modern optical-field engineering for ultrafast laser processing.

Artificial intelligence-assisted approaches provide additional opportunities for adaptive optimization of ultrafast laser processing. By combining machine-learning algorithms with differentiable optimization, inverse design, and neural-network-based methods, it becomes possible to identify optimized optical-field configurations and laser-processing parameters within high-dimensional parameter spaces, reducing experimental effort compared with conventional experimental optimization strategies. Integration of machine-learning algorithms with process monitoring and digital-twin concepts may further enable closed-loop optimization, where processing conditions are continuously adjusted based on experimental feedback. Such adaptive strategies represent an important step toward autonomous ultrafast laser processing platforms capable of compensating process variations and improving reproducibility across different materials and fabrication tasks [30,52,111,118].

6.3. Future Architectures

Future optical-field engineering architectures are expected to combine multiple control mechanisms into compact and adaptive systems. Programmable metasurfaces and integrated photonic components provide promising opportunities for manipulating phase, polarization, and spectral properties of ultrashort laser pulses while reducing the complexity of conventional optical arrangements [44,74,115]. These approaches may enable more compact and robust architectures by integrating optical-field generation and control functions within a single platform. Such developments are particularly relevant for future ultrafast laser systems requiring reduced alignment complexity and enhanced adaptability.

Hybrid architectures combining static optical elements, programmable modulators, holographic field synthesis, and computational optimization offer a potential route toward scalable and versatile ultrafast laser manufacturing systems [51,113]. By combining the efficiency and robustness of passive components with the flexibility of programmable control, such systems may enable dynamic adaptation of optical fields according to material properties, structural requirements, and processing objectives.

Ultimately, the future development of optical field engineering will rely on the integration of advanced optical architectures, computational intelligence, and adaptive laser-matter interaction control. The transition toward autonomous and application-specific ultrafast laser manufacturing platforms represents a key direction for achieving higher efficiency, improved reproducibility, and expanded functionality in micro- and nanofabrication, supporting predictive and application-driven surface engineering.

7. Conclusions

Ultrafast optical field engineering has emerged as a key strategy for advancing laser micro- and nanofabrication beyond the limitations of conventional single-spot scanning approaches. The ability to control temporal, spatial, and spatiotemporal characteristics of ultrashort laser fields provides new opportunities for precise energy delivery, improved process stability, and enhanced fabrication throughput. Recent developments demonstrate a transition from isolated pulse- and beam-shaping techniques toward integrated optical architectures capable of dynamically adapting laser fields to specific processing requirements.

Temporal pulse shaping approaches based on programmable waveform control, combined with adaptive optimization and advanced photonic structures, enable precise manipulation of excitation dynamics and nonlinear light–matter interactions. In parallel, spatial beam-shaping technologies based on spatial light modulators, digital micromirror devices, diffractive optical elements, holographic methods, and hybrid optical systems provide flexible control over intensity distributions, focal architectures, and parallel processing strategies. Together, these approaches establish a comprehensive framework for engineering ultrafast optical fields across multiple degrees of freedom.

The comparison of different optical architectures reveals a fundamental trade-off between flexibility, optical efficiency, power-handling capability, and system complexity. Static refractive and diffractive elements offer high efficiency and robustness for stable industrial processing, whereas programmable systems provide superior adaptability and dynamic control. Hybrid architectures combining passive and active optical components represent a promising pathway toward scalable ultrafast manufacturing by integrating the advantages of both approaches.

Applications of optical field engineering have demonstrated improvements in high-throughput microfabrication, three-dimensional structuring, functional surface modification, photonic device fabrication, and precision joining technologies. However, further progress requires overcoming challenges related to optical losses, computational complexity, high-power operation, and the nonlinear response of processed materials. Future developments will increasingly rely on the integration of adaptive optics, artificial intelligence, real-time process monitoring, and material-specific optimization strategies.

Despite these advances, several challenges remain for the industrial integration of optical-field engineering. The scalability of parallel processing is limited by available laser power, optical damage thresholds, field reconstruction accuracy, and computational complexity. Further progress requires improved understanding of nonlinear laser–matter interactions and deeper integration of adaptive optics, in situ diagnostics, artificial intelligence, and digital-twin-based optimization for application-specific ultrafast laser manufacturing.

Overall, ultrafast optical field engineering provides a foundation for the next generation of laser manufacturing systems, enabling the transition from conventional beam delivery toward intelligent, adaptive, and parallel processing platforms. The continued convergence of advanced optical architectures, computational design methods, and laser–matter interaction science is expected to further expand the capabilities of ultrafast laser micro- and nanofabrication and support its broader adoption in industrial applications.

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