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Advances in Femtosecond Laser Micro-Nano Machining for Optical Microstructure Fabrication

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Abstract. Ultrafast femtosecond lasers feature ultrashort pulses, ultrahigh peak power and cold ablation, and have evolving into a vital precision machining tool in optoelectronic engineering. This paper reviews femtosecond laser fabrication of optical microstructures including microlens arrays, photonic crystals and micrograting. It elaborates the cold processing mechanism of femtosecond lasers and analyzes how laser energy, scanning speed and repetition rate modulate microstructure morphology. Domestic and international mainstream process optimization strategies are compared, and existing bottlenecks such as low machining efficiency and surface microdefects are summarized. The research verifies that proper matching of laser parameters with an assistive gas atmosphere remarkably reduces microstructural defects and improves optical transmittance. Finally, this work sorts out current research trends and proposes feasible paths to balance processing quality and efficiency, offering references for high-precision manufacturing of functional optical microdevices.

Keywords: laser, micro-nano processing, optical microstructures, optoelectronic devices

1. Introduction

Fueled by the rapid evolution of integrated photonic chips, AR/VR devices and high-power laser systems, the global market demand for miniaturized optical microstructures with ultrahigh machining precision has witnessed steady growth. Conventional manufacturing techniques including photolithography and mechanical machining are restrained by narrow material compatibility and limited forming accuracy, making them incapable of fabricating three-dimensional buried microstructures embedded inside transparent dielectric substrates. As an emerging ultrafast laser technology, femtosecond laser cold ablation achieves nearly thermal-damage-free material removal and is compatible with almost all types of optical materials, thus occupying an irreplaceable position in the field of micro-nano optoelectronics [1].

Nevertheless, most domestic existing research concentrates solely on processing experiments of a single material, lacking systematic comparative investigations into multi-dimensional process parameter systems. This paper is structured into four core sections. The first elaborates the fundamental physical principles of femtosecond laser micromachining. The second analyzes how key process parameters modulate the final forming quality of optical microstructures. The third

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summarizes representative applications of femtosecond laser-fabricated functional microstructures. The fourth discusses prevailing technical bottlenecks and corresponding optimization strategies.

Based on a comprehensive literature comparative analysis method, this review systematically sorts out cutting-edge research progress in femtosecond laser microfabrication. The conclusions drawn in this work can provide meaningful references for the localization of domestic ultrafast laser processing equipment and the large-scale mass production of integrated optoelectronic chips.

1.1. Characteristics of femtosecond ultrafast lasers

A femtosecond laser emits ultrashort pulses with durations on the femtosecond scale ($1\ \mathrm{fs}=10^{-15}\ \mathrm{s}$), featuring ultra-short pulse duration, ultrahigh peak power and broad spectral bandwidth. Its ultrashort pulses confine light-matter interaction within ultrafast relaxation scales. Following Fourier transform theory, shorter pulses correspond to wider spectra. These unique properties create extreme physical conditions unattainable by conventional long-pulse lasers during material interaction.

1.2. Nonlinear ionization and cold ablation mechanisms

The mechanism of femtosecond laser cold ablation relies on nonlinear energy absorption and non-equilibrium energy relaxation during laser-matter interaction. Driven by multiphoton ionization and tunneling ionization, intense pulses generate dense plasma without relying on linear material absorption, enabling processing of wide-bandgap dielectrics. Its pulse duration is shorter than the electron-phonon coupling time. As described by the two-temperature model, electrons heat rapidly while the lattice remains cool. Material removal occurs via Coulomb explosion and phase explosion before substantial thermal diffusion, yielding minimal heat-affected zones and ultrahigh precision.

1.3. Comparison of processing features: femtosecond laser and nanosecond laser

Table 1. Comparison of processing characteristics between femtosecond laser and nanosecond laser [2]

Comparison Dimension	Femtosecond Laser	Nanosecond Laser
Pulse Width	Femtosecond scale ($1\ \mathrm{fs}=10^{-15}\ \mathrm{s}$)	Nanosecond scale ($1\ \mathrm{fs}=10^{-15}\ \mathrm{s}$)
Peak Power	Extremely high	Relatively low
Energy Absorption Mechanism	Nonlinear absorption (multiphoton ionization, tunneling ionization)	Linear absorption (heat conduction, melting)
Heat-Affected Zone	Extremely small (nanoscale) with nearly no thermal damage	Large (micron scale), accompanied by obvious melting, recast layers and thermal cracks
Machining Precision & Quality	Ultrahigh precision with smooth edges and no burrs; submicron precision available	Relatively low precision, rough edges and severe thermal deformation
Stress Mechanism	Ultrahigh instantaneous thermal stress enabling interface separation	Accumulated thermal stress prone to macroscopic material cracking

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Table 1. (continued)

Material Compatibility	Applicable to nearly all materials (metals, semiconductors, dielectrics)	Poor performance for highly reflective and highly transparent materials
Residues	Extremely low; e.g., only 0.54% residue after aluminum film etching	Abundant residues requiring post-processing
Machining Efficiency	Low single-pulse ablation rate, compensated by high repetition frequencies (MHz, GHz-burst)	High single-pulse ablation rate, yet thermal effects restrict precision machining

Table 1 compares femtosecond and nanosecond lasers in nine aspects. Benefiting from the cold ablation mechanism based on nonlinear multiphoton absorption, femtosecond lasers achieve superior machining precision, negligible thermal damage and wide material adaptability. However, their low single-pulse removal efficiency limits processing throughput, requiring high-repetition-rate operation for speed improvement. By contrast, nanosecond lasers realize high single-pulse ablation rates via linear thermal melting, but severe thermal defects impair surface accuracy. They still possess prominent cost and stability advantages for rough micro-machining applications.

2. Process parameter effects on optical microstructure quality

2.1. Laser energy: tuning rules for ablation depth and edge burrs

Laser energy dominates the fabrication quality of optical microstructures and regulates ablation depth and edge burrs regularly. Laser power primarily governs material removal depth; excessive power intensifies thermal effects and induces molten accumulation. Energy density determines surface morphology in femtosecond laser machining. Although ultrashort pulses suppress thermal diffusion, molten residues emerge above a critical energy threshold. Edge burr formation is closely related to energy density and pulse width. Hybrid ion beam etching, as well as picosecond lasers replacing nanosecond lasers, can mitigate thermal damage and reduce edge irregularities for improved structural quality.

2.2. Scanning speed and repetition rate: control methods for surface roughness

Scanning speed and repetition rate [3] jointly determine laser spot overlap and spatiotemporal energy distribution, serving as critical factors controlling surface roughness. Scanning speed exerts the most prominent influence: surface roughness declines first and then rises with increasing speed. Repetition rate ranks second; moderate values homogenize surfaces, yet excessive repetition. Optimized parameter sets for laser surface texturing and femtosecond laser finishing are verified experimentally to achieve desirable surface morphology.

2.3. Auxiliary processing conditions: gas environment and substrate material matching

Auxiliary processing conditions significantly affect the forming quality of optical microstructures. Reasonable shielding gas, such as an inert gas, suppresses oxidation, plasma shielding and debris re-deposition during laser machining. Substrates exhibit distinct laser absorptivity and thermal diffusion properties, which dominate processing outcomes. Optimized laser parameters for stainless steel, aluminum alloy, TC4 titanium alloy and WC/Co cemented carbide are concluded from

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experiments. Lasers with different pulse widths bring varied material responses. Picosecond lasers cause less damage to stainless steel, while nanosecond lasers yield higher surface hardness. Suitable pulse widths should be chosen based on practical machining demands.

2.4. Comparative morphology analysis of microstructures

Multi-parameter optimization is critical for high-quality microstructure fabrication. Orthogonal experiments clarify parameter weights, while grey relational analysis realizes multi-objective optimization to obtain optimal processing parameters. Nanosecond, picosecond and femtosecond lasers differ greatly in thermal effects. Femtosecond lasers enable genuine cold machining with minimal heat-affected zones and superior precision. Ion-beam-assisted laser hybrid processing addresses poor dimensional controllability of microstructures fabricated by nanosecond lasers. Modeling the evolution of micro-pit profiles achieves controllable high-quality microtexture fabrication on cemented carbides, offering a novel route for precision forming of optical microstructures.

3. Applications of typical optical microstructures fabricated by femtosecond lasers

3.1. Microlens arrays for laser displays and beam shaping

Microlens arrays are vital optical components for laser displays, beam shaping and optical imaging, whose machining determines light modulation performance. Femtosecond lasers fabricate such arrays via direct writing combined with selective HF etching. Focus scanning induces material modification, and differential etching forms spherical or aspherical microlenses. Benefiting from minimal heat-affected zones, this technique achieves submicron precision and smooth surfaces. These arrays homogenize Gaussian beams, improve light efficiency, and can be fabricated on curved and flexible substrates, broadening applications in freeform optics.

3.2. Photonic crystal waveguides embedded in fused silica

Photonic crystal waveguides precisely control light propagation via photonic band gaps and serve as essential devices for integrated photonics, quantum communication and optical interconnection. Conventional technologies struggle to fabricate embedded 3D waveguides inside fused silica,which can be solved by femtosecond laser direct writing. Tightly focused pulses trigger nonlinear absorption to induce permanent refractive index modulation. Controlled 3D scanning enables arbitrary embedded photonic crystal structures. Such buried waveguides avoid surface scattering, support flexible 3D layouts and realize low-loss coupling with single-mode fibers. This technique exhibits promising prospects in quantum photon manipulation, on-chip optical interconnection and optical computing chips.

3.3. Micro-grating structures for laser interferometric detection

Micrograting are crucial components for precision displacement measurement and laser interferometry, whose fabrication accuracy determines system resolution. Femtosecond lasers produce micrograting via two approaches: interferometric patterning with tunable grating periods and flexible point-by-point direct writing. As measuring scales in interferometric systems, such gratings enable nanoscale displacement detection with stable performance. Compared with holographic exposure and mechanical scribing, femtosecond laser processing features mask-free

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fabrication and flexible structural design. It can create volume gratings inside transparent materials. Benefiting from minimal thermal defects, the fabricated micrograting possess high laser-induced damage thresholds, satisfying the requirements of high-power interferometric detection systems.

4. Current technical bottlenecks and optimization schemes

4.1. Existing core problems: low batch machining efficiency and residual micro-defects after ablation

Although femtosecond laser cold ablation delivers unparalleled precision for optical microstructure fabrication, two critical bottlenecks hinder its practical industrial deployment.

First, batch machining throughput remains low. Femtosecond pulses only carry microjoule-to-millijoule energy, and serial point-by-point scanning leads to extremely long processing cycles for large-area microlens arrays, photonic crystal networks and dense microgratings, often requiring dozens of hours or even days. This restricts mass manufacturing. Even two-photon polymerization suffers from prolonged fabrication, causing structural instability and limiting widespread adoption of complex 3D microdevices [4]. Single-beam machining also fails to meet high-volume microhole array demands.

Second, ablation-induced residual microdefects cannot be fully eliminated despite cold-processing traits. Under high fluence or repetition rates, recast melt accumulates at feature edges and impairs optical performance. Fluctuating laser energy, focal drift and material inhomogeneity degrade surface roughness and raise scattering loss. Excessive energy density also triggers subsurface microcracks and residual stress, lowering long-term stability and laser damage threshold of optical components. Such defects create gaps between actual and theoretical optical performance, which severely impairs high-precision laser interferometry and laser display systems.

4.2. Optimization strategies: AI-based parameter prediction and multi-beam parallel machining

To tackle the above challenges, researchers and industries have proposed various optimization approaches, among which AI parameter prediction and multi-beam parallel processing show promising prospects.

Laser machining involves numerous parameters with complicated nonlinear coupling, making the trial-and-error method inefficient. Machine learning methods such as artificial neural networks and support vector machines build mapping models between processing parameters and machining performance. Combined with genetic algorithms and particle swarm optimization, these models predict ablation depth and surface roughness, and rapidly search for optimal parameter sets.

Trained on experimental datasets, the neural network learns nonlinear relationships [5]. It forecasts machining outcomes for new parameter combinations, drastically cutting experimental costs and facilitating high-quality femtosecond laser cold ablation.

4.3. Future development trends of hybrid processing technology

Single laser machining cannot simultaneously deliver high efficiency, precision and minimal damage, making hybrid processing a core trend for femtosecond laser cold ablation. Typical hybrid schemes cover laser-ultrasonic, laser-chemical and laser-EDM machining, plus multi-energy field assistance. Laser-ultrasonic vibration suppresses thermal defects and microcracks in brittle optical

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materials [6]. Laser-induced modification paired with HF wet etching eliminates molten residues for ultra-smooth 3D microstructures, and ion-beam assistance will further refine structural accuracy. Laser-EDM hybrid processing enables high-precision shaping and functional coating for conductive optical molds. Auxiliary electric, magnetic and thermal fields regulate plasma behavior and reduce thermal stress during ablation.

Future systems will integrate Industry 4.0 intelligence and digital twins. Digital twin models support real-time monitoring, simulation and adaptive control. Machine learning optimizes parameters online, while in-situ OCT and spectral sensors build closed-loop feedback to stabilize machining quality.

Advanced manufacturing is advancing toward high-speed, hybrid and intelligent fabrication for micro and large-scale components. Hybrid, intelligent and high-throughput femtosecond laser cold ablation will facilitate mass production of optical microdevices, precision optics and biomedical microstructures.

5. Conclusion

Femtosecond ultrafast lasers stand out as an irreplaceable tool for fabricating high-precision optical microstructures, attributed to their intrinsic merits of ultrashort pulses, ultrahigh peak power and cold ablation mechanism. Unlike nanosecond lasers that cause severe thermal damage, femtosecond lasers rely on multiphoton and tunneling ionization to trigger non-thermal material removal via Coulomb and phase explosion, yielding nanoscale heat-affected zones, submicron machining accuracy and compatibility with almost all optical materials ranging from metals to wide-bandgap dielectrics such as fused silica and sapphire.

This paper systematically summarizes three mainstream femtosecond-laser-fabricated optical microdevices: microlens arrays, embedded photonic crystal waveguides and functional microgratings. Each component meets distinct demands in beam homogenization, on-chip quantum photonics and nanometric displacement respectively. Key processing parameters including laser energy, scanning speed and pulse repetition rate jointly govern ablation depth, surface roughness and edge quality, while auxiliary shielding gas and substrate matching further suppress oxidation, debris re-deposition and surface flaws. Multi-objective optimization combining orthogonal experiments and grey relational analysis can efficiently screen optimal parameter combinations to balance machining quality.

Nevertheless, two dominant bottlenecks restrict industrial mass production: low throughput from serial point-by-point scanning and ablation-induced residual microdefects including melt accumulation and subsurface cracks. Two promising solutions are reviewed herein: AI-driven parameter prediction that eliminates repetitive trial-and-error tests, and multi-beam parallel processing that drastically lifts batch efficiency. Looking ahead, hybrid multi-energy-field machining integrated with digital twin monitoring and closed-loop feedback control will dominate future development. Combined laser-ultrasonic, laser-chemical and ion-beam-assisted composite processing effectively mitigates thermal defects and enables complex 3D embedded microstructures.

Overall, the integration of femtosecond cold ablation, intelligent algorithm optimization and multi-energy hybrid techniques will advance the large-scale manufacturing of miniature optical chips, AR/VR components and high-power laser optical elements, providing solid technical support for next-generation integrated photonic systems.

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