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From Macro to Micro: Multimode Fiber Lasers in Direct Laser Interference Patterning

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Abstract

This study introduces a pioneering advancement in Direct Laser Interference Patterning (DLIP) through the integration of a high-power multimode pulsed nanosecond fiber laser, for high-precision microfabrication processes. By employing an innovative beam-shaping approach using the Extended Laser Interference Patterning System (ELIPSYS®) from SurFunction GmbH, the inherent limitations of low coherence and beam quality in multimode lasers are effectively addressed. This novel configuration enabled the generation of precise, well-defined periodic line-like microstructures with a periodicity of 24 µm and aspect ratios up to 0.8, while maintaining a significant deep focus range of approximately 0.6 mm, which is crucial for large-area applications. The impact of critical laser parameters, specifically pulse energy and pulse-to-pulse overlap, on the resulting structure depth and uniformity of the structures is comprehensively investigated. Confocal microscopy characterization confirmed an optimal processing window, balancing structure depth and uniformity across patterned surfaces. These findings demonstrate the feasibility and significant potential of coupling high-power multimode fiber lasers with DLIP technology, enhancing process efficiency and scalability while opening new opportunities for integrating these versatile and high-power lasers into industrial-scale microfabrication that demands high precision and throughput over large areas.

Keywords: Direct laser interference patterning, ELIPSYS system, high-power multimode fiber laser, surface micro processing, periodic line-like structures;

1. Introduction

Laser-based surface texturing has emerged as a key technology for functionalizing material surfaces by producing textured surfaces with feature sizes in the micro- and nanoscales, enabling applications ranging from tribological control to wettability tuning and biological interactions (Chen et al., 2022). Among the various techniques available, Direct Laser Interference Patterning (DLIP) stands out for its ability to generate large-area periodic structures with high precision and throughput (Lasagni et al., 2017). By overlapping two or more coherent laser beams, DLIP produces a stationary interference pattern that can be transferred directly onto the material surface, producing well-defined and controllable patterns in a single step.

Historically, DLIP has utilized pulsed solid-state lasers due to their high spatial and temporal coherence, which are critical for generating stable and high-contrast interference patterns (Lasagni and Voisiat, 2024). These systems typically rely on free-space optical arrangements, including mirrors and lenses, to scale and direct the laser beam to a specific DLIP configuration (module). However, such configurations demand meticulous alignment and are sensitive to beam-pointing instabilities, particularly over long beam paths. These limitations compromise patterning accuracy and hinder integration into automated or robotic manufacturing systems commonly used for processing complex geometries.

In addition, addressing industrial requirements for high-throughput and large-area surface structuring requires increased laser power. While single-mode solid-state lasers can deliver generally up to 300 - 600 W of laser power, surpassing this threshold generally requires the implementation of multimode fiber lasers (Ränke et al., 2024; Zervas and Codemard, 2014). In addition to high power, these sources offer several operational advantages such as a more stable performance, and enhanced durability. Furthermore, their fiber-based delivery architecture provides flexible beam transport, making them compatible with robotic systems and dynamic industrial environments. However, due to their high M² factor (low beam quality), the beams produced in multimode lasers can not be focused to small spot sizes as effectively as those from single-mode lasers, making them unsuitable for micropatterning applications. Additionally, their low spatial and temporal coherence, along with random polarization, have traditionally been viewed as fundamental limitations for DLIP, where high interference contrast is essential.

This study presents a groundbreaking advancement in DLIP processing by integrating a high-power (1 kW) multimode nanosecond fiber laser (IPG Photonics) with an Extended Laser Interference Patterning System (ELIPSYS®, SurFunction GmbH). This novel configuration, despite the coherence and beam quality limitations already mentioned above, successfully generated a two-beam interference pattern with an spatial period of 24 µm. To the best of our knowledge, this is the first demonstration of using a multimode fiber laser for microstructuring using DLIP. This capability significantly expands the operational flexibility and throughput of DLIP, while also opening new market opportunities for high-power multimode pulsed laser manufacturers.

2. Material and methods

A newly developed optical head based on the ELIPSYS® technology (SurFunction GmbH) was developed to enable the formation of precise interference patterns using a multimode fiber laser (YLPN-100-20×40×100-1000-R, IPG Photonics), despite its comparatively low beam quality ($M^2 = 50$) and random polarization. The laser operated at a wavelength of 1064 nm, with a pulse duration of 20 ns, delivering pulse energies up to 50 mJ at frequencies ranging from 2 to 20 kHz, achieving a maximal average power of 1 kW. Within the optical head, the laser beam was split, shaped, and focused to produce an elliptical spot exhibiting a periodic line-like intensity profile, yielding a spatial period (Λ) of 24.0 µm over a 2716 × 261 µm² area (~0.56 mm²).

DLIP experiments were conducted on cleaned stainless-steel plates (1.4301, 1.0 mm thickness) with an initial surface roughness (Sq) of 52 nm. The samples were mounted on an XY motion stage (Aerotech Inc.) and translated parallel to the interference fringes, perpendicular to the major axis of the laser spot, throughout the laser patterning process, as shown in Fig. 1. Key processing parameters, including positioning speed (25–500 mm/s) and pulse energy (10–50 mJ), were systematically varied keeping the laser repetition rate constant at 2 kHz. The variation of scanning speed directly affected the pulse overlap (O_p) along the structuring direction, which is expressed as:

$$O_p = 100\left(1 - \frac{d_{st}}{d}\right), \qquad (1)$$

where d_{st} represents the distance between consecutive pulses and d is the spot dimension along the scan direction (261 µm).

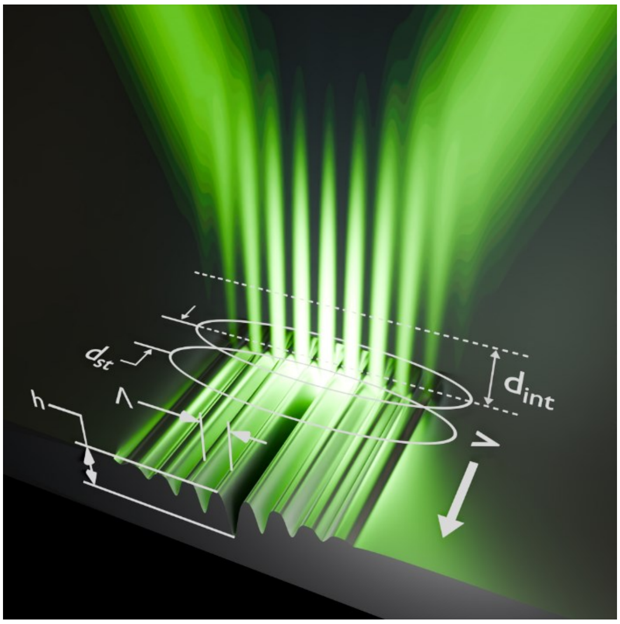

Fig. 1. Schematic representation of the DLIP strategy performed for structuring the stainless steel samples.

The topography of the structured samples was measured using a confocal microscope (Sensofar S Neox 3D Surface Profiler) with 50x objective, achieving 170 nm lateral and 3 nm vertical resolution. The topography data were then processed in SensorMap® 7.4 software using ISO 16610-14 and ISO 25178-2 standards to extract the average structure height (*h*) and root-mean-square height parameter (S_q), which quantify depth and its deviation (Wang et al., 2025).

3. Results and discussions

3.1. Analysis of the formed laser spot

Prior to the ablation experiments, the optical head's laser output was characterized by measuring the laser spot spatial profile using a WinCamD-LCM camera (DataRay Inc.) coupled with a 20x microscope objective. The elliptical laser spot, measuring 2716 × 261 µm², exhibited clear periodic interference fringes, as illustrated in Fig. 2a and 2d, thus confirming successful multimode laser interference. When measurements were conducted at distances away from this interference plane (Fig. 2b and 2c), the interference fringes became progressively blurred with increasing distance. The corresponding cross-sectional intensity profiles, taken from the central region of the spot and presented in Figs. 2d-f, distinctly reveal a reduction in interference contrast. This rapid deterioration in fringe contrast is attributable to the limited coherence length characteristic of multimode lasers (Takahara, 1982).

A detailed investigation of contrast dependency as a function of distance from the interference plane, previously reported by Wang et al., 2025, demonstrated that interference contrast experiences a reduction of no more than 10% within a 0.6 mm range (see d_{int} in Fig. 1). This capability is highly beneficial for processing complex geometries, thereby extending the applicability of multimode fiber lasers for intricate and large-area surface treatments.

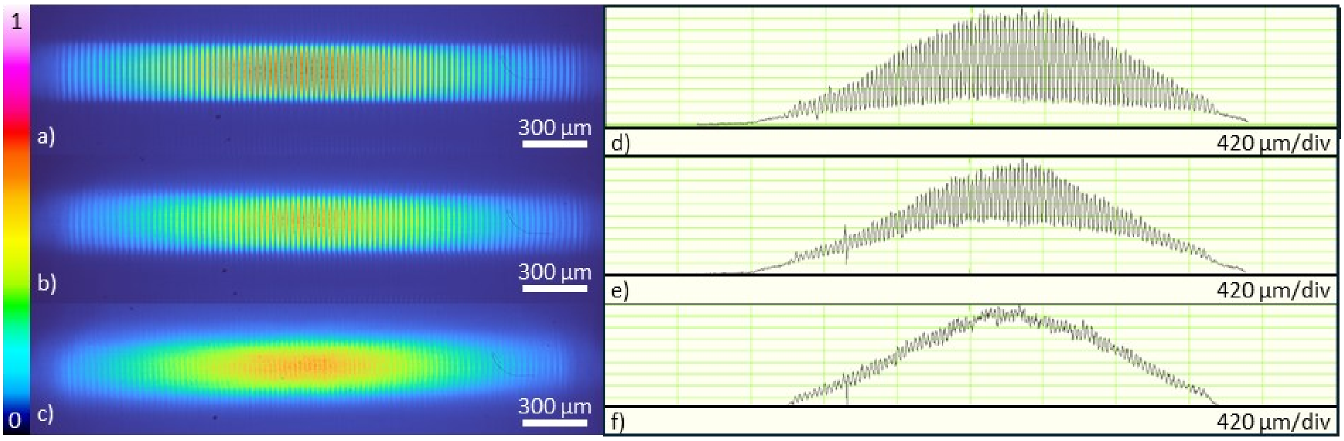

Fig. 2. Interference spot intensity profiles measured at different distances from the interference plane: (a) at the plane, (b) 0.5 mm away, (c) and 1.0 mm away. Corresponding cross-sectional intensity profiles from the central region of the spot are shown on the right (d–f).

3.2. Influence of process parameters on microstructure formation

After performing the characterization of the interference patterns, ablation experiments on the stainless-steel surface was performed at a constant repetition rate of 2 kHz while systematically varying pulse energy and scanning speed. The resulting surface topographies featured well-defined periodic microstructures composed of parallel ridges and valleys, as depicted in Fig. 3a (confocal microscope images). Measurements confirmed that the periodicity of the ablated patterns accurately matched the 24.0 µm spacing of the generated interference intensity distribution, thereby verifying precise spatial control and stable interference conditions.

Detailed analysis, however, revealed that the depth and morphology of the produced structures were influenced significantly by the processing parameters, in particular pulse energy and pulse-to-pulse overlap. Fig. 3b illustrates a representative topography exhibiting substantial depth variations, attributed primarily to the uneven redistribution of resolidified molten material originating from the intensity maxima regions and accumulating in the intensity minima areas. In Fig. 3c, also locally variations of the line-like pattern geometry are visible arising specifically from excessively low pulse overlap, which similarly compromise the uniformity of the produced structures. Both phenomena highlight the critical role of precise adjustment and optimization of laser processing parameters to ensure consistently high-quality microstructuring.

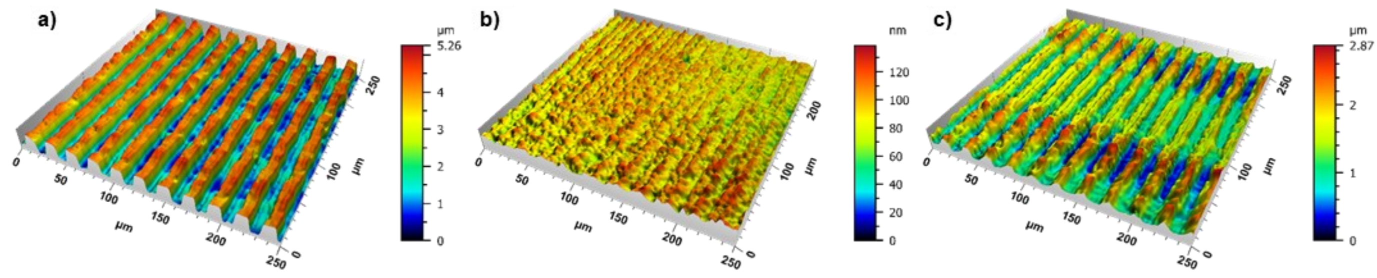

Fig. 3. Confocal microscopy images of DLIP structures fabricated using a multimode fiber laser. Topographies correspond to different combinations of pulse energy (Ep) and pulse-to-pulse overlap (Op): (a) O_p = 80.8%, E_p = 35 mJ; (b) O_p = 61.7%, E_p = 25 mJ; (c) O_p = 42.5%, E_p = 35 mJ.

The average structure depth was systematically measured as a function of pulse energy and pulse overlap, and the results are presented in Fig. 4 as a 3D surface plot illustrating their combined influence on the fabricated structures. Additionally, the color scale overlay on the 3D surface indicates the corresponding structural quality, represented by the relative standard deviation of the structure depth compared to the mean depth, allowing an easy identification of optimal processing conditions. The results indicate an operational window characterized by minimal structural variations, specifically where the relative depth deviation remains below 15% (blue-colored area), centered around a pulse overlap of approximately ~81% and pulse energy of 35 mJ. Notably, the deepest structure achieved, with a depth of about 18.7 µm and corresponding to an aspect ratio of 0.8, was obtained at a pulse overlap of 95.2% and pulse energy of 30 mJ. Further detailed analysis and additional insights into these structural characteristics are provided in Wang et al., 2025.

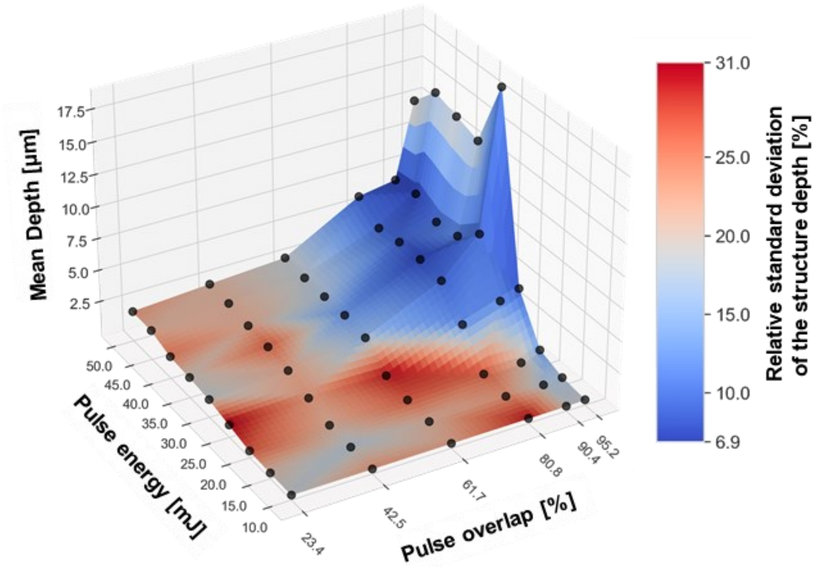

Fig. 4. 3D surface plot showing the dependence of average structure depth on pulse energy and pulse-to-pulse overlap. The overlaid color map represents the relative depth variation across the measured area.

4. Conclusion

This work demonstrated, for the first time, the successful integration of Direct Laser Interference Patterning (DLIP) with a high-power multimode nanosecond fiber laser. Utilizing the ELIPSYS® beam-interference module, line-like periodic structures with a spatial period of 24.0 µm and aspect ratios up to 0.8 were fabricated, while maintaining a relatively large effective interference depth of 0.6 mm. A systematic analysis of pulse energy and pulse-to-pulse overlap revealed an optimal process window for achieving high-quality and uniform microstructures. These findings highlight the potential of this configuration for large-area and complex-surface texturing, offering a scalable and robust solution for industrial applications. The flexibility, stability, and power scalability of fiber lasers make this approach highly promising for high-throughput laser-based manufacturing.

Acknowledgements

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