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## ABSTRACT

In this work, we introduce a simple and universal optical setup design for laser surface texturing (LST) that provides functionality superior than direct laser interference patterning (DLIP). The method requires only a single periodic diffractive optical element and a focusing lens while enabling unlimited freedom for spatial shaping and amplitude variations. The concept is based on the special behavior of diffraction gratings when illuminating an area on the grating that is close in size to a single period rather than effectively infinite periods as is usually discussed in fundamental grating studies. Empirical optimization for a specific ratio value of grating period and incident laser beam size was done on a two-dimensional intensity distribution by fitting the one-dimensional intensity profile to a periodical squared cosine function. We investigate the design characteristics and tolerance sensitivity for this work regime and discuss some application ideas including practical example suggestion of optical design, and some tailored patterning capabilities allowed by the method. A detailed comparison was made between DLIP setup and the proposed alternative method for LST.

Key words: direct laser interference patterning, diffractive optical element, laser surface texturing, beam shaping, optical system design



## I. INTRODUCTION

Patterning the surfaces of different materials by laser surface texturing (LST) has great economic and ecological potential by adding application-tailored surface properties such as increase or reduction of friction, hydrophoby, increased light scattering, etc. Some examples of treated devices include[1] hydraulics,[2] seals,[3–5] thrust bearing,[6] magnetic storage devices,[7] MEMS devices,[8] engines,[9] and bone and dental implants.[10,11] Products with modified surfaces can have longer lifetimes, improved ease of cleaning and lower friction.

The continuously growing availability of laser power enables laser processing of progressively larger areas, while maintaining LST advantages of precision, dry environment, microscale features, and geometry flexibility.

Direct laser interference patterning (DLIP) is one among several laser techniques used to process large areas with high speed. Unlike single laser[12–14] scanning methods, DLIP patterns an entire area using a single pulse with a surface period that is a function of the angle of interfering beams and laser wavelength. This method offers unparalleled flexibility in terms of patterned period, as well as a large focal depth, but requires a rather complex and tolerance sensitive setup.

## II. THEORETICAL BACKGROUND

In prior publications about DLIP, the authors[15–17] used multi-element setups where an incident beam was split into sub-beams (typically 4), then the sub-beams were individually redirected by refractive or reflective[18] optics to be parallel, and finally, all sub-beams were focused on the target plane.

An advanced setup demonstrated by El-Khoury *et al.*[19] included an additional Top Hat beam shaper placed before the beam splitter to improve the intensity uniformity of the patterned features, HAZ (heat affected zone) referred to area where intensity did not reach process threshold and converted to unwanted heat effect, and another advantage in process speed.

The main limitations of these classical solutions are assembly complexity of elements without rotational symmetry (beam shaper, beam splitter, and prism) and limited freedom of modification (fixed beam size of beam shaper, and pattern geometry defined by beam splitter configuration and fitted prism). The typical DLIP setup shown in Fig. 1(a) includes a high-power short pulse pico- or femtosecond laser, a variable beam expander, a high-power diffractive optical element (DOE) beam splitter to split the incident beam into two or more beams, a collimating prism for split diffraction orders, and a high NA focusing objective.

The alternative setup we suggest shown in Fig. 1(b) is well known in laser industrial applications.[20] It includes the same laser as the DLIP setup, a variable beam expander for precise beam size adjustment, a single DOE beam splitter that creates an interference pattern in the image plane, and an *F*-theta scanner. Only small adaptations are required to convert an existing industrial laser machines to DLIP applications. The key difference between standard parallel processing systems used in a similar configuration[21–23] and our concept is that the goal of the suggested solution is to modify entire surface area characteristics by tailored surface patterning instead of discrete spots. This is achieved by certain criteria that will be discussed in Sec. II.

The diffractive beam splitter used in the proposed setup is a periodic phase grating element that splits an incident beam into a predefined configured of diffraction orders. The design of the element is done by iterative Fourier transform algorithm (IFTA).[24] This algorithm allows one to obtain a desired far field diffraction order configuration with individual control of the intensity of each diffracted order. In the far field, one obtains well separated diffraction limited beams.

The grating theory used to analyze such gratings assumes that an infinite number of periods are illuminated uniformly by the incident light, i.e., a ratio approaching 0 between the grating period and the beam size. When this ratio increases significantly above 0, special phenomena appear in the output light field.

Specifically, in illumination for our LST method, we use a special, empirically discovered, ratio between the incident beam size and the grating period size. The performance condition is to find a value when diffraction orders are well separated but still close. This state occurs on the border between periodical gratings like diffractive beam splitters and non-periodical beam shaping solutions like Top Hat beam shapers. For odd numbers of split diffractive orders, this ratio is about 0.65, as we will show.

For all simulations in the article, we used the same parameters: wavelength of 1064 nm, beam size of 8 mm, effective focal length (EFL) of 30 mm, and a diffraction limited spot size of 5.1 $\mu$m. For propagation, we used the physical optic angular spectrum propagation method that is most suitable to show interference phenomena. This propagation method is widely used for laser optical system design and simulation and is commonly used[25] by commercially optical design software.

In our first simulation, example in Fig. 2, we show the effect of using different ratios of beam size to period size on an example of $15 \times 15$ diffraction orders created by a single beam splitter DOE at the focal plane of a focus lens. It can be seen that for large ratios 0.7 and 0.65 of beam size to period size, spots in the array are well packed and even have some overlapping, and for smaller ratios of 0.6 and 0.55, the fill factor decreases. On the other hand, smaller fill factor designs deliver better depth of focus (DOF). The depth of focus is defined as the *z* distance when orders are still separated. In all ratios, the resulting intensity envelope is Top Hat shaped since all diffractive orders are designed with the same intensity without the need for any special Top Hat beam shaper as is required to achieve similar results in DLIP.

As a second case study to find the optimal ratio between beam and grating period size, we simulated the intensity in the focal plane for a one-dimensional beam splitter with 15 orders and fitted it to a squared cosine function. The squared cosine function was chosen because it describes the optimal surface topography for many DLIP LST applications.[26] In Figs 3(a)–3(d), we show that best results in terms of squared cosinelike intensity profiles are achieved by this same ratio of 0.65 between beam size and DOE beam splitter period size. A ratio of 0.55 has better fit close to local extremum of the periodic function, but when comparing the overall fit quality, the better ratio is 0.65. In Fig. 3, we confirm the results quantitatively by comparing the integrated difference between the intensity distribution and the squared cosine function.

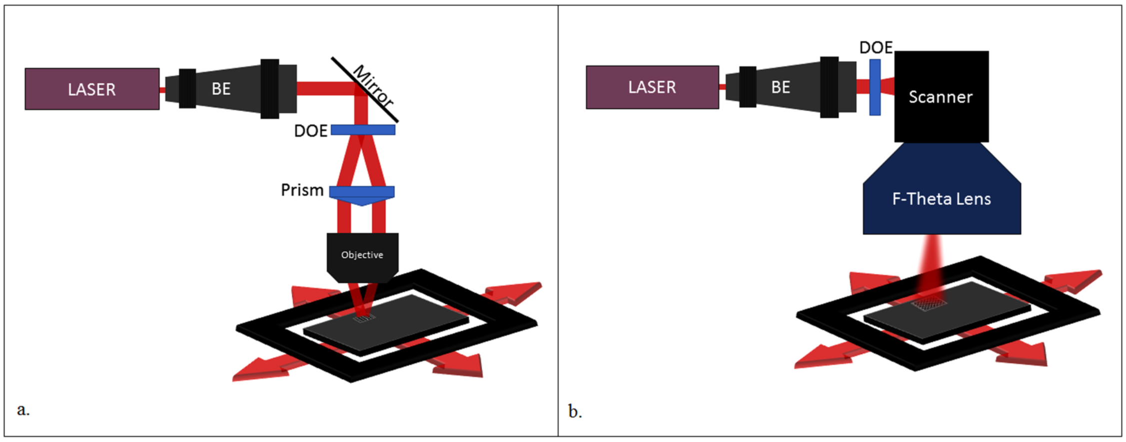


**FIG. 1.** (a) Typical DLIP setup. (b) Suggested optical setup alternative to DLIP for LST. A special LST DOE is placed between a beam expander and a scanner.

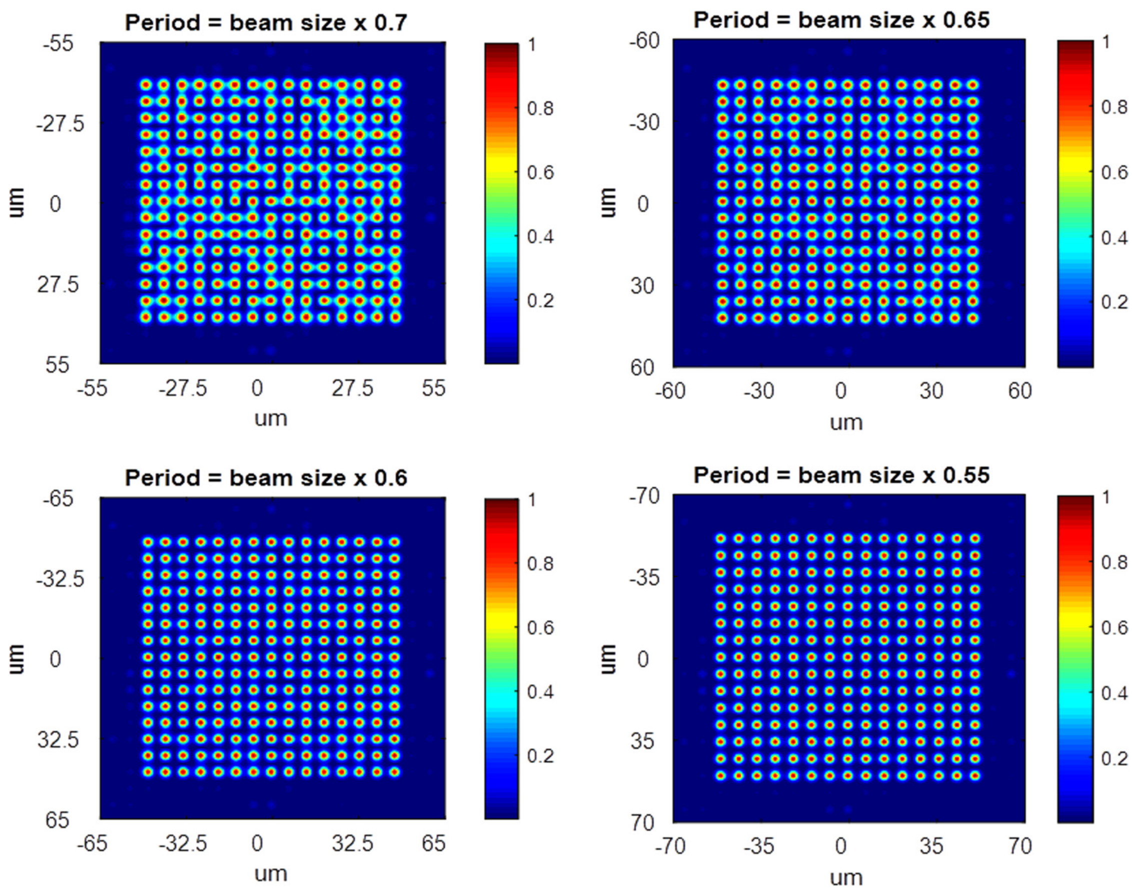


FIG. 2. Effect of ratio between beam size and DOE beam splitter period size. The compromise is between better depth of focus for smaller periods and better fill factor for larger periods' size.

It is important to note that for certain applications, other ratios may be preferred. Still, the general optical design remains the same.

In Fig. 4, we show the effect of the beam size versus period size ratio on the DOF. Even a small difference in period has a strong effect. On the demonstrated examples, DOF of setup with a period equal to 0.5 beam size is almost twice than for a period equal to 0.65 beam size.

## III. PRACTICAL ADVANCED EXAMPLE FOR LARGE AREA STRUCTURING

The LST concept we present here can easily accommodate large area structuring, as the number of orders in the beam splitter can easily be greater than 1000. Let us review a case where the pattern period is a typical $6\,\mu$m (useful for super-hydrophobic surfaces[27]). To cover an area of $12 \times 12\,\text{mm}^2$ with a $6\,\mu$m pitch, we would need a DOE beam splitter with $2001 \times 2001$ orders.

Assuming a focus lens with EFL = 100 mm, such a beam splitter would have a period of 17.7 mm, i.e., using the 0.65 ratio, we would need a beam of 27.2 mm diameter. These parameters are readily available in standard off-the-shelf *F*-theta lenses. The DOE itself would have an easily producible full angle of 6.8°, allowing for efficient multilevel solutions incorporating zero order elimination techniques.[28] The power densities on the DOE for this LST method are relatively low, as the beam size is very large, and high-power fused silica DOE element can easily withstand typical LST high-power densities and pulse energies, as shown in the work of previous authors for the $2 \times 2$ diffractive beam splitter DLIP setup discussed earlier.

## IV. MORE EXAMPLES OF LST

In this section, we present some examples to show that our suggested structuring method enables freedom to generate intensity distribution of any level of complexity. In Fig. 5(a), we show the possibility to control processed and unprocessed regions without energy loss. Figure 5(b) shows a hexagonal order distribution that has a better fill factor relatively to square one. Figures 5(c) and 5(d)

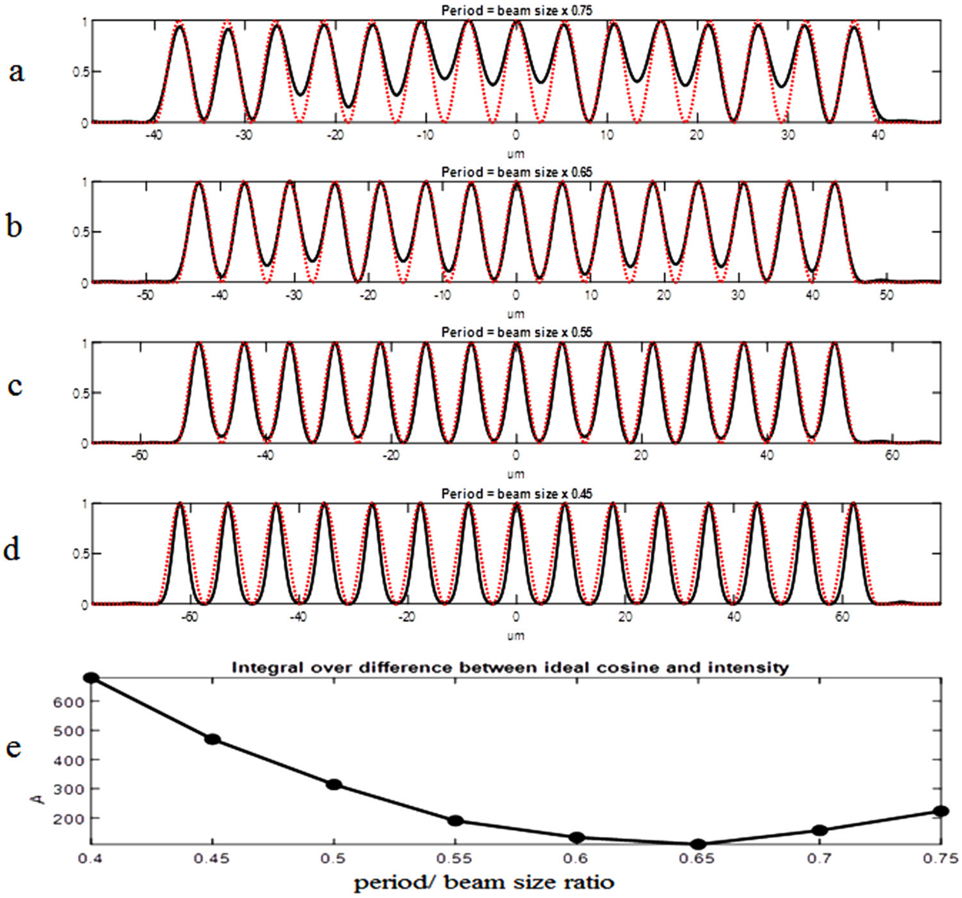


**FIG. 3.** (a)–(d) Intensity profile of 1D beam splitter of 15 spots for constant incident beam size and variation of period size. (e) The integrated difference between intensity and squared cosine function as a function of the ratio between period and beam size. In this parabola like plot, the minima value is at a ratio equal to 0.65.

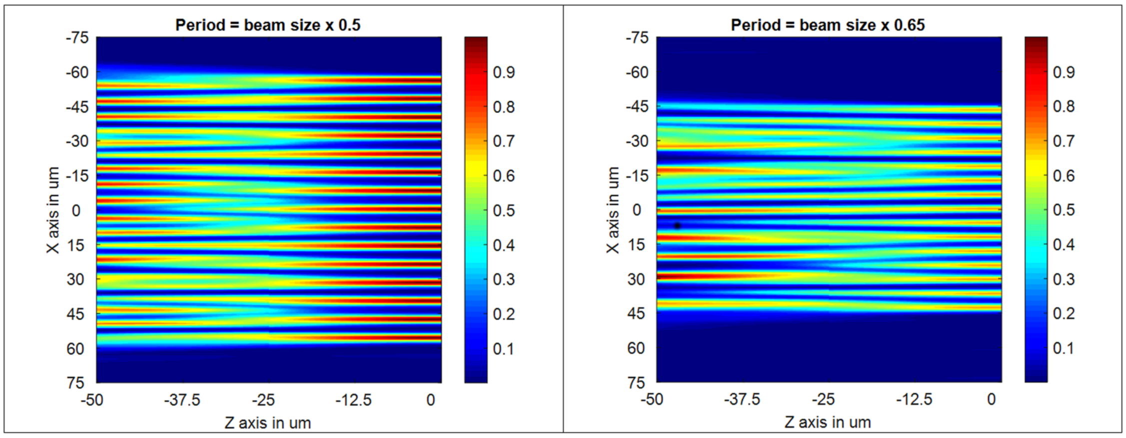


**FIG. 4.** Depth of focus analysis near the focal position for two values of ratio between period size and beam size. Zero position refers to the focal plane. Smaller ratios lead to larger depth of focus.

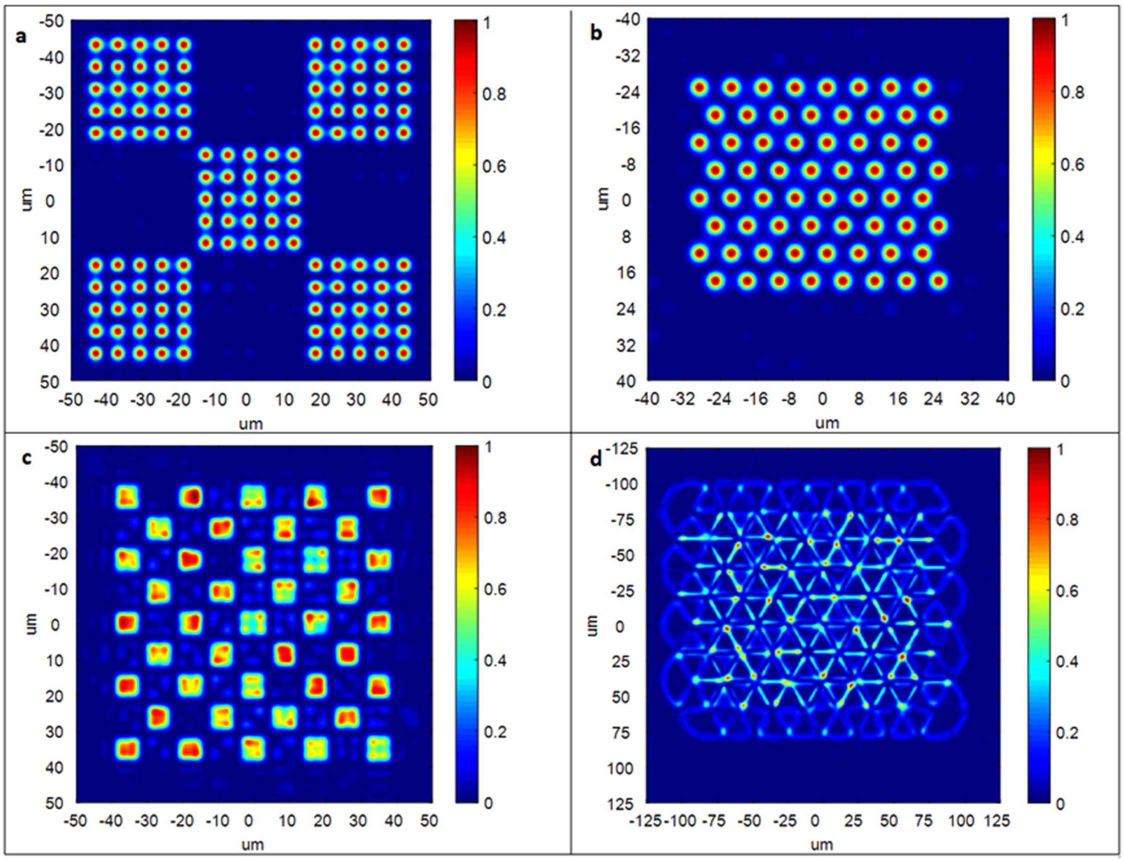


**FIG. 5.** (a) Image shows a kind of chess like structuring. Structured cells include 5 × 5 well defines gaussian microstructures. (b) Image shows a hexagonal lattice structure including 64 gaussian shaped microstructures. (c) Image shows intensity distribution of combination between a hexagonal beam splitter and a small square beam shaper. (d) Image shows skin like intensity distribution generated by a combination of hexagonal beam splitter and Axicon with certain relation of periods.

show example of combining semiperiodic optical shaping and nonperiodic functionalities (Top Hat shaper and Axicon).

## V. COMPARISON TO DLIP

The proposed optical setup benefits from significantly lower alignment sensitivity compared to DLIP—it is basically completely insensitive to the centering of the periodic DOE relative to the beam, unlike DLIP where beam centering on the prism is critical.

The DOE can have a large period (small diffraction angles) and benefits from higher manufacturing precision and high efficiency options by manufacturing multilevel or kinoform diffractive patterns. The efficiency can reach 90%. In contrast, a binary four beams DOE beam splitter used in DLIP has nominal 65% efficiency.

Another important quality parameter is uniformity between orders. For most cases, we expect uniformity contrast less than 10%. The fact that a small number of periods is illuminated by the beam does not have a significant effect on output intensity.

The focusing optics used for our DOE based LST method are *F*-theta commonly used in industrial applications. As the method does not utilize the full scanning field such lenses allow, it can be used with higher NA than normally allowed when scanning, enabling patterning pitches of 6 $\mu$m and even less.

One important aspect where our LST structuring is limited relative to DLIP is in pitch flexibility. While for DLIP, a variation in surface pitch can be easily carried out by adjusting the relative beam angles, our LST method is limited to a certain pitch that is predefined by the DOE separation angle and the focusing optics.

This issue can be mitigated by replacing the DOE per-process or by adding a variable telescope between the DOE and the focusing optics, allowing one to apply scaling to the pattern, including the pitch. However, for most industrial applications, the need for flexibility is limited, and a certain fixed pitch per DOE is quite workable.

## VI. SUMMARY AND CONCLUSIONS

In the article, we presented a robust light structuring method that can be used as a DLIP alternative for LST applications. The idea is to use a periodic DOE with a specific beam size in order to reach the optimal fill factor over the processed area. This method has obvious advantages over DLIP methods with multiple interfered beams, including better uniformity, higher efficiency, better HAZ, lower assembly complexity, greater shaping freedom, and lower system costs. As a practical case, we discussed high density patterning over a large area using our method and showed it to be feasible. Following this, we showed a few examples of custom shapes with orthogonal and hexagonal feature distributions and advanced shapes of combined functions of beam splitters and beam shapes.

We believe that the simplification of LST systems using our approach could be attractive in many applications as an alternative to DLIP, especially in industrial applications, where there is less need of flexible variation of the pitch and where reliability and simplicity are of high value.

## ACKNOWLEDGMENT

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## REFERENCES


[1]A. F. Lasagni *et al.*, "Direct laser interference patterning, 20 years of development: From the basics to industrial applications," SPIE Proc. **10092**, 1009211 (2017).

[2]Jian Zhan and Mingjiang Yang, "Investigation on dimples distribution angle in laser texturing of cylinder–piston ring system," Tribol. Trans. **55**, 693–697 (2012).

[3]Tao Wang, Weifeng Huang, Xiangfeng Liu, Yongjian Li, and Yuming Wang, "Experimental study of two-phase mechanical face seals with laser surface texturing," Tribol. Int. **72**, 90–97 (2014).

[4]Shaoxian Bai, Xudong Peng, Yefeng Li, and Songen Sheng, "A hydrodynamic laser surface-textured gas mechanical face seal," Tribol. Lett. **38**, 187–194 (2010).

[5]Andriy Kovalchenko, Oyelayo Ajayi, Ali Erdemir, and George Fenske, "Friction and wear behavior of laser textured surface under lubricated initial point contact," Wear **271**, 1719–1725 (2011).

[6]Victor Brizmer, Yuri Kligerman, and Izhak Etsion, "A laser surface textured parallel thrust bearing," Tribol. Trans. **46**, 397–403 (2003).

[7]Bart Raeymaekers, Izhak Etsion, and Frank E. Talke, "Enhancing tribological performance of the magnetic tape/guide interface by laser surface texturing," Tribol. Lett. **27**, 89–95 (2007).

[8]K. Komvopoulos, "Adhesion and friction forces in microelectromechanical systems: Mechanisms, measurement, surface modification techniques, and adhesion theory," J Adhes. Sci. Technol. **17**, 477–517 (2003).

[9]I. Etsion and E. Sher, "Improving fuel efficiency with laser surface textured piston rings," Tribol. Int. **42**, 542–547 (2009).

[10]D. Günther, Dieter Scharnweber, Ricarda Hess, Cornelia Wolf-Brandstetter, M. Grosse Holthaus, and Andrés Lasagni, "High precision patterning of biomaterials using the direct laser interference patterning technology," in *Laser Surface Modification of Biomaterials* (Woodhead, Sawston, Cambridge, UK, 2016), pp. 3–33.

[11]Denise Guenther *et al.*, "Direct laser interference patterning for decreased bacterial attachment," SPIE Proc. **9736**, 973611 (2016).

[12]Stefan Rung, Kevin Bokan, Frederick Kleinwort, Simon Schwarz, Peter Simon, Jan-Hendrik Klein-Wiele, Cemal Esen, and Ralf Hellmann, "Possibilities of dry and lubricated friction modification enabled by different ultrashort laser-based surface structuring methods," Lubricants **7**(5), 43 (2019).

[13]M. Martínez-Calderon, M. Manso-Silván, A. Rodríguez, M. Gómez-Aranzadi, J. P. García-Ruiz, S. M. Olaizola, and R. J. Martín-Palma, "Surface micro-and nano-texturing of stainless steel by femtosecond laser for the control of cell migration," Sci. Rep. **6**, 36296 (2016).

[14]Antonio Riveiro, Anthony L. B. Maçon, Jesus del Val, Rafael Comesaña, and Juan Pou, "Laser surface texturing of polymers for biomedical applications," Front. Phys. **6**, 16 (2018).

[15]E. Stankevičius, M. Gedvilas, B. Voisiat, M. Malinauskas, and G. Račiukaitis, "Fabrication of periodic micro-structures by holographic lithography," Lith. J. Phys. **53**, 227–237 (2013).

[16]Sabri Alamri, Fotis Fraggelakis, Tim Kunze, Benjamin Krupop, Girolamo Mincuzzi, Rainer Kling, and Andrés Fabián Lasagni, "On the interplay of DLIP and LIPSS upon ultra-short laser pulse irradiation," Materials **12**(7), 1018 (2019).

[17]Sebastian Eckhardt, Mathias Siebold, and Andrés Fabián Lasagni, "Laser microstructured metal thin films as promising alternative for indium based transparent electrodes," Opt. Express **24**, A553–A568 (2016).

[18]Alexander Peter, Volkher Onuseit, Christian Freitag, Sebastian Faas, and Thomas Graf, "Flexible, compact and picosecond laser capable four-beam interference setup," Zenodo. https://doi.org/10.5281/zenodo.2583582.

[19]Mikhael El-Khoury, Bogdan Voisiat, Tim Kunze, and Andrés-Fabián Lasagni, "Utilizing fundamental beam-mode shaping technique for top-hat laser intensities in direct laser interference patterning," J. Laser Micro Nanoeng. **13**, 268–272 (2018).

[20]Gerald F. Marshall and Glenn E. Stutz, *Handbook of Optical and Laser Scanning* (CRC, Boca Raton, FL, 2016).

[21]L. Büsing, S. Eifel, and Peter Loosen, "Design, alignment and applications of optical systems for parallel processing with ultra-short laser pulses," SPIE Proc. **9131**, 91310C (2014).

[22]Barthels, T., M. Reininghaus, and H. Westergeling, "High-precision ultrashort pulsed laser drilling of micro and nano holes using multibeam processing," SPIE Proc. **11107**, 111070K (2019).

[23]Oskar Hofmann, Jochen Stollenwerk, and Peter Loosen, "Design of multi-beam optics for high throughput parallel processing," J. Laser Appl. **32**, 012005 (2020).

[24]Ralph W. Gerchberg, "A practical algorithm for the determination of phase from image and diffraction plane pictures," Optik **35**, 237–246 (1972), available at http://www.u.arizona.edu/~ppoon/GerchbergandSaxton1972.pdf.

[25]J. Schmidt, "Numerical simulation of optical wave propagation with examples in MATLAB," Society of Photo-Optical Instrumentation Engineers, 2010.

[26]Andreas Rosenkranz, Michael Hans, Carsten Gachot, Adrian Thome, Simon Bonk, and Frank Mücklich, "Direct laser interference patterning: Tailoring of contact area for frictional and antibacterial properties," Lubricants **4**(1), 2 (2016).

[27]P. Hauschwitz, R. Jagdheesh, S. Alamri, D. Rostohar, T. Kunze, J. Brajer, J. Kopeček, and T. Mocek, "Fabrication of functional superhydrophobic surfaces on carbon fibre reinforced plastics by IR and UV direct laser interference patterning," Appl. Surface Sci. **508**, 144817 (2019).

[28]S. Katz, N. Kaplan, and I. Grossinger, "Diffractive optical elements: Minimizing zero order," Photon. Spectra **52**, 50–53 (2018), available at https://www.photonics.com/Articles/Related_Diffractive_Optical_Elements_Minimizing/ar62935.