Perspective

Quo Vadis LIPSS?—Recent and Future Trends on Laser-Induced Periodic Surface Structures

Jörn Bonse

Bundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87, D-12205 Berlin, Germany; joern.bonse@bam.de; Tel.: +49-30-8104-3562

Received: 2 September 2020; Accepted: 29 September 2020; Published: 30 September 2020

Abstract: Nanotechnology and lasers are among the most successful and active fields of research and technology that have boomed during the past two decades. Many improvements are based on the controlled manufacturing of nanostructures that enable tailored material functionalization for a wide range of industrial applications, electronics, medicine, etc., and have already found entry into our daily life. One appealing approach for manufacturing such nanostructures in a flexible, robust, rapid, and contactless one-step process is based on the generation of laser-induced periodic surface structures (LIPSS). This Perspectives article analyzes the footprint of the research area of LIPSS on the basis of a detailed literature search, provides a brief overview on its current trends, describes the European funding strategies within the Horizon 2020 programme, and outlines promising future directions.

Keywords: laser-induced periodic surface structures (LIPSS); ripples; applications; direct laser interference patterning (DLIP); surface functionalization; literature survey; review articles; special issues; scientific workshops; European funding strategies

1. Introduction

During the last five decades, laser-induced periodic surface structures (LIPSS) have gained remarkable attention and developed into a scientific evergreen [1]. This is based on the simplicity and robustness of the single process step required for their manufacturing that can be performed in ambient air and that is fully compatible with industrial demands on costs, reliability, and productivity. Depending on the selected materials and specific irradiation conditions, the processing of LIPSS enables a large variety of various types of surface functionalization that become possible through different feature sizes, ranging between a few tens of nanometers up to several micrometers. This allows for addressing many applications in the fields of optics, electronics, fluidics, mechanical engineering, and medicine [2–6].

LIPSS are an arrangement of (quasi)periodic topographic lines representing a linear surface grating structure. They can be classified according to their spatial periods (λ) and the orientation to the linear laser beam polarization used for their generation [1]. Many variants in naming the phenomenon of LIPSS can be found in the literature: some authors refer to ripples, or nanoripples, or even to near-wavelength or deep-subwavelength structures. Note that sometimes, other types of surface structures, such as hexagonally arranged nanometric protrusions or so-called micrometric Grooves or Spikes [7], are also referred to as LIPSS.

Figure 1a provides the common classification of different types of grating-like LIPSS observed upon irradiation with ultrashort laser pulses. Low spatial frequency LIPSS (LSFL) have periods larger than half the laser irradiation wavelength (λ). They are either perpendicular (LSFL-I) or parallel (LSFL-II) to the laser beam polarization, depending on their specific formation mechanism [1,8]. An example of the LSFL-I type structures on the surface of Ti:sapphire femtosecond (fs-) laser-irradiated Ti6Al4V titanium alloy surface is provided in Figure 1b.
2. Analysis of the Research Area of LIPSS

2.1. Available Literature

2.1.1. Peer Reviewed Articles (1982–2020)

The current situation in the research area of LIPSS was analyzed through a literature search in the “ISI Web of Science—Core Collection” database, performed on 3 August 2020. In order to optimize the quality of the results, the precise search term “Laser-induced Periodic Surface Surface Structures” was used...
in the category “Topic”, since the alternative term “Ripples” or other variants turned out to be too unspecific and generated too many incongruous hits. Based on this search strategy, 1111 publications were identified. The set of these publications is further analyzed in the following.

Figure 2 shows the number of annually published papers vs. the publication year since the term LIPSS was launched in the scientific literature by van Driel and co-workers in 1982 [10]. Already, during the first half of the 1980s, groundbreaking research was performed and published by two North American groups around van Driel and Sipe [10–13] in Canada, and around Fauchet and Siegman [14,15] in the USA. It included already time-resolved studies on the formation of LIPSS and material specific fundamental theories of these surface structures. That knowledge, based mainly on nanosecond (ns-) laser generated LIPSS, was summarized in some excellent review articles [16–19]. At that time, not too many questions were left open since the near-wavelength-sized LIPSS (LSFL) usually observed for ns-laser irradiation were successfully explained. Since industrially relevant applications were not developed, the academic interest on LIPSS dropped again, and during the 1990s, rather constant research activities with less than ten papers published per year can be seen in Figure 2. That situation changed around the turn of the millennium, caused by the discovery of a new type of LIPSS with sub-wavelength characteristics (HSFL) that were observed upon irradiation with ultrashort laser pulse durations in the picosecond (ps-) to fs-range. This trend, visible in the rising publication rate, was supported by the increasing availability of ultrashort laser systems and is still ongoing with currently more than 130 publications per year.

![Graph showing research activities in the area of LIPSS](image)

**Figure 2.** Research activities in the area of LIPSS, exemplified by the number of papers published per year—matching on 3 August 2020 in the “ISI Web of Science—Core Collection” database to the search term “Laser-induced Periodic Surface Structures”.

The same set of data was analyzed with regard to geographical origins of the 1111 publications. Figure 3 visualizes, in a map of the world, the sixteen countries being most active in LIPSS research along with the associated absolute number of the publications originating from them. The inset in the lower left corner orders these countries according to the corresponding percentage when relating the absolute number of publications to the total number in the data set. Note that the sum of percentages (number of papers) exceeds 100% (1111) since a publication may arise from international collaborations of research groups assigned to different countries.
While early research on LIPSS was mainly performed in North America, currently, the most intense activities are located in Europe, China, Japan, and Russia.

The largest number of articles was published from groups from China (242), followed by Germany (209), the USA (147), Japan (102), France (74), Spain (66), Russia (63), Czech Republic (49), Italy (45), Canada (43), England (34), Austria (33), India (30), Singapore (27), South Korea (25), and the Netherlands (24). While early research on LIPSS was mainly performed in North America, currently, the most intense activities are located in Europe, China, Japan, and Russia.

Table 1 lists the research institutions publishing most actively in the field of LIPSS, ordered by the number of publications and the corresponding percentages. The top three (and, in total, five out of the top ten institutions) represent national research academies/councils that confine publications of multiple different groups working on LIPSS.

Table 1. Top 10 international research institutions with publications associated to the scientific topic of LIPSS, evaluated on basis of the “ISI Web of Science” database 1.

| Institution                                                                 | Country | Number of Papers 1 | Percentage 1 |
|----------------------------------------------------------------------------|---------|--------------------|--------------|
| Centre National de la Recherche Scientifique, CNRS                          | FR      | 60                 | 5.4%         |
| Chinese Academy of Sciences                                                 | CN      | 54                 | 4.9%         |
| Consejo Superior de Investigaciones Científicas, CSIC                        | ES      | 53                 | 4.8%         |
| Bundesanstalt für Material-forschung und -prüfung, BAM                      | DE      | 49                 | 4.4%         |
| Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie, MBI    | DE      | 40                 | 3.6%         |
| Russian Academy of Sciences, RAS                                             | RU      | 36                 | 3.2%         |
| University of Rochester                                                     | USA     | 34                 | 3.1%         |
| Czech Academy of Sciences, CAS                                               | CZ      | 31                 | 2.8%         |
| CNRS Institute for Engineering Systems Sciences, INSIS                       | FR      | 30                 | 2.7%         |
| Université Jean Monnet Saint-Étienne                                         | FR      | 30                 | 2.7%         |

1 Search in “ISI Web of Science—Core Collection” database, 3 August 2020, search term “Laser-induced Periodic Surface Structures” in “Topic”, identifying a set of 1111 publications.

The top 10 scientific journals and corresponding publishers with articles in the area of LIPSS are provided in Table 2, ordered by the number of publications and the corresponding percentages.
Most publications appeared in the journal *Applied Surface Science* (167, 15%), followed by the *Proceedings of SPIE* (95, 8.6%), *Applied Physics A* (69, 6.2%), *Journal of Applied Physics* (48, 4.3%), *Applied Physics Letters* (40, 3.6%), *Optics Express* (40, 3.6%), *Journal of Laser Micro/Nanoengineering* (25, 2.3%), and three other journals with less than 2% contained in the analyzed data set. According to the scope of these journals, the publications are interdisciplinary and mainly associated with research areas of physics, material science, optics, chemistry, technology, and engineering.

**Table 2.** Top 10 scientific journals and publishers with articles associated to the scientific topic LIPSS, evaluated on basis of the “ISI Web of Science” database.

| Journal                                      | Publisher          | Number of Papers | Percentage |
|----------------------------------------------|--------------------|------------------|------------|
| Applied Surface Science                      | Elsevier           | 167              | 15.0%      |
| Proceedings of SPIE                         | SPIE 2             | 95               | 8.6%       |
| Applied Physics A                           | Springer Nature    | 69               | 6.2%       |
| Journal of Applied Physics                  | AIP 3              | 48               | 4.3%       |
| Applied Physics Letters                     | AIP 3              | 40               | 3.6%       |
| Optics Express                              | OSA 4              | 40               | 3.6%       |
| Journal of Laser Micro/Nanoengineering      | JLPS 5             | 25               | 2.3%       |
| Physical Review B                           | APS 6              | 19               | 1.7%       |
| Optics and Laser Technology                 | Elsevier           | 18               | 1.6%       |
| Optics Letters                              | OSA 4              | 18               | 1.6%       |

1 Search in “ISI Web of Science—Core Collection” database, 3 August 2020, Search term “Laser-induced Periodic Surface Structures” in “Topic”, identifying a set of 1111 publications. 2 Society of Photo-Optical Instrumentation Engineers. 3 American Institute of Physics. 4 Optical Society of America. 5 Japan Laser Processing Society. 6 American Physical Society.

2.1.2. Review Articles

The state of knowledge on LIPSS up to the middle of the 1980s was reviewed by different groups [16–18]. The renewed and increased attention to LIPSS at the turn of the millennium has led to numerous new experimental findings featuring the capabilities of ultrashort laser pulses, i.e., enabling a non-equilibrium between the electronic system and the lattice system of irradiated solids. Through tailored energy deposition via polarization-controlled double-fs-pulse sequences [20], or in time-resolved coherent scattering [21,22], diffraction [23] and microscopy [24] experiments, important new insights were gained on the early stage of LIPSS formation, particularly on the relevance and involvement of surface plasmon polaritons (SPPs)—for details, see [1].

Other review articles [25,26] discussed the similarity and relation between the HSFL and some volumetric nanostructures observed upon focusing a fs-laser beam tightly into the bulk of transparent dielectrics [27]. The direct link between both types of structure could finally be provided though time-resolved 3D finite-difference time-domain (FDTD) numerical simulations, identifying the non-radiative near-field scattering at nanoscopic defects as shared origin [8].

Very recently, the competition between electromagnetic models and matter reorganization theories was reviewed [28]: in view of 3D-FDTD simulations combined with a two-temperature model, the equation-of-state, and the Navier–Stokes equations [29], it can be stated that two classes of theories (electromagnetics vs. hydrodynamics) currently merge into a joint view on LIPSS, allowing to consider both the early electromagnetic excitation and energy deposition and the following matter reorganization stages.

A still-ongoing and very active trend in the research of LIPSS is the study of their applications for various surface functionalizations since LIPSS can modify the optical, mechanical, and chemical properties of irradiated surfaces for industrial applications in optics, tribology, medicine, etc. Up-to-date surveys on this topic are found in recent reviews articles [2–5]. Many applications are particularly inspired by nature and enable surface engineering through tailored biomimetic laser-generated surface structures, reviewed in [6,30].
2.1.3. Special Issues

Various peer-reviewed scientific journals have recognized the potential of the topic and organized Special Issues related to LIPSS. Table 3 lists a selection that is ordered chronologically. Most of them are currently arranged by the publisher MDPI that is even running several topically overlapping issues at the same time.

Table 3. Special issues related to LIPSS published in peer-reviewed scientific journals.

| Journal                              | Publisher         | Special Issue                                                                 | Date |
|--------------------------------------|-------------------|-------------------------------------------------------------------------------|------|
| Journal of Laser Applications        | LIA 1             | “Generation of sub-100 nm Structures by Nonlinear Laser Material Interaction” | 2012 |
| Optical Materials Express           | OSA 2             | “Ultrafast Laser Modification of Materials (ULM)”                            | 2013 |
| MRS Bulletin                         | MRS 3             | “Ultrafast Laser Synthesis and Processing of Materials”                       | 2016 |
| Nanomaterials                        | MDPI 4            | “Laser-Based Nano Fabrication and Lithography”                                | 2018 |
| Opto-Electronic Advances             | IOE-CAS 5         | “IAPLE Special Issue of Opto-Electronic Advances”                            | 2019 |
| Optical Materials Express           | OSA 2             | “Laser Writing”                                                               | 2019 |
| Lubricants                           | MDPI 4            | “Laser-Induced Periodic Surface Nano- and Microstructures for Tribological Applications” | 2020 |
| Advanced Optical Technologies       | De Gruyter        | “Laser Micro- and Nano-Material Processing”                                   | 2020 |
| Nanomaterials                        | MDPI 4            | “Laser-Generated Periodic Nanostructures”                                    | 2020 |
| Nanomaterials                        | MDPI 4            | “Laser Synthesis and Modification of Materials at the Nanoscale”             | 2020 |
| Nanomaterials                        | MDPI 4            | “Laser Printing of Nanophotonic Structures”                                  | 2020 |
| Nanomaterials                        | MDPI 4            | “Femtosecond Laser Micro/Nanofabrication”                                    | 2020 |
| Nanomaterials                        | MDPI 4            | “Laser Surface Functionalization on Nanomaterials”                           | 2021 |
| Nanomaterials                        | MDPI 4            | “Nanopatterning of Bionic Materials”                                         | 2021 |

1 Laser Institute of America. 2 Optical Society of America. 3 Materials Research Society. 4 Multidisciplinary Digital Publishing Institute. 5 Institute of Optics and Electronics, Chinese Academy of Sciences.

2.2. Scientific Conferences and Workshops

The most important conferences in the field of laser–matter interaction nowadays all organize individual sessions devoted to LIPSS. The most relevant ones are the biannual International Conference on Laser Ablation (COLA), the annual Spring Meeting of the European Materials Research Society (E-MRS), the annual International Symposium on Laser Precision Microfabrication (LPM), several symposia at the annual SPIE Photonics West Conference, the annual Conference on Lasers and Electro-Optics (CLEO®), the International High Power Laser Ablation Symposium (HPLA), the annual International Conference on Advanced Laser Technologies (ALT), the triannual International Symposium “Fundamentals of Laser Assisted Micro- and Nanotechnologies” (FLAMN), the biannual International Conference on Photo-Excited Processes and Applications (ICPEPA), and the annual industry near International Congress on Applications of Lasers and Electro-Optics (ICALEO®), among some other smaller conferences.

Since approximately ten years ago, a highly specialized, invitation-based International Workshop on Laser-Induced Periodic Surface Structures (LIPSS) has been organized by Europe’s LIPSS community, typically with only 20–40 attendees to keep the format informal, allowing to stimulate in-depth discussions. It was initiated in 2011 by the University of Twente (The Netherlands) and later organized in Germany, Czech Republic, France, Greece, and Slovenia. Table 4 recalls its history until today.

In 2017, an additional public workshop, Laser Processing for Bionic Applications, was organized at BAM for the dissemination of a European research project (LiNaBioFluid, see Section 3.5) to an international industrial and academic audience.
3. Recent (Ongoing) Trends

This section elucidates some recent trends in the field of LIPSS, discussing current theoretical and surface analytical developments, a comparison to alternative surface processing techniques, most recent applications, and a view on the European research landscape of LIPSS.

3.1. Electromagnetics vs. Matter Reorganization

During the past two decades, there was a vivid and stimulating discussion regarding the origin of LIPSS, particularly whether these structures are caused via ultrafast energy deposition mechanisms that are acting during the absorption of optical radiation, or via matter reorganization effects that are occurring after the irradiation process [1]. Taking advantage of the ultrashort pulse duration available in the fs- to ps-range, time-resolved approaches based on coherent scattering [21], diffraction [23], microscopy [24], and polarization-controlled multi-wavelength double-fs-laser pulse irradiation [20] have experimentally proven about ten years ago that the ultrafast excitation stage is essential for the formation of LIPSS upon ultrashort pulse laser irradiation. Recently, however, important improvements were made regarding the theoretical modeling, particularly via electromagnetic FDTD, [31,32] and hydrodynamic [29,33] and molecular dynamics (MD) simulations [34,35] considering post-irradiation matter reorganization. Currently, both theoretical approaches, i.e., electromagnetics and matter reorganization, are merging into a joint view where—depending on the irradiation conditions and materials—specific electromagnetic/reorganization aspects can dominate. A detailed review is provided in [28].

3.2. Topography vs. Chemistry

There is an ongoing and vivid debate on the relevance of chemical effects accompanying the formation of LIPSS. It is triggered by the fact that many applications of LIPSS, e.g., for surface wetting control, cell and bacterial adhesion, or the management of friction and wear, are affected by both the sample topography and the local surface chemistry. While most of the early research focused mainly on topographical effects, currently, the influence of the surface chemistry is increasingly investigated [9,36–39], studying, in detail, superficial oxidation upon irradiation in air environment and post-irradiation molecular adsorption phenomena.

Depth-resolved surface analytical studies on LIPSS based on Auger electron microscopy (AEM) [9], time-of-flight secondary ion mass spectrometry (TOF-SIMS) [40], and glow-discharge optical emission spectroscopy (GD-OES) [41] indicate a graded oxidized surface layer of several hundreds of nanometer thickness. Such nanostructured oxide layers may, however, exhibit beneficial tribological effects, particularly in combination with “anti-wear” additives, such as zinc-dialkyl-dithiophosphate (ZDDP), contained in lubricants, such as commercial engine oil [41–43].
The impact of laser processing on surface wetting behavior became more clear already ten years ago through a study of Kietzig et al. [44], reporting that metal surfaces are superhydrophilic (water contact angles ~ 0°) right after laser irradiation of different types of surface structures (LIPSS, Grooves, Spikes) due to laser-induced oxidation. On the timescale of several days or even longer, and without any topographic changes, the surfaces turn nearly superhydrophobic (water contact angles > 150°) due to the adsorption of hydrocarbon molecules or other contaminants from the ambient environment [44–46]. Since the presence of adsorbed molecules or contaminants at the surface is not necessarily stable against the storage conditions, surface cleaning, heat treatment [46], and other ageing effects, reliable industrial applications of these structures are difficult and may require additional stabilization steps.

3.3. LIPSS vs. DLIP

Another method for producing line grating like periodic surface structures relies on direct laser interference patterning (DLIP) by superimposing two focused laser beams at the sample surface. Figure 4 compares the processing of LIPSS by using a Galvanometer scanner and an f-Theta lens (Figure 4a) with the more complex DLIP setup (Figure 4b), where an additional grating interferometer is employed to realize the two-beam interference here [47].

![Setup LIPSS processing](image1.png) ![Setup DLIP processing](image2.png)

**Figure 4.** Different approaches for generating grating-like periodic surface structures. (a) Setup for processing of LIPSS. (b) Setup for direct laser interference patterning (DLIP) processing. Abbreviations: HWP: half-wave plate; THG: third harmonic generator; BET: beam expanding telescope; reprinted from Rung et al. [47], Possibilities of Dry and Lubricated Friction Modification Enabled by Different Ultrashort Laser-Based Surface Structuring Methods, *Lubricants*, 2019, 7, 43. Copyright 2019 under Creative Commons BY 4.0 license. Retrieved from https://doi.org/10.3390/lubricants7050043.

When choosing proper laser pulse energies for DLIP, material removal (ablation) is caused selectively at the interference maxima of the spatially modulated intensity distribution generated by the two incident laser beams visualized in Figure 5a. The spatial period (λ_{DLIP}) of the interference pattern can be controlled by the laser wavelength (λ) and the angle of incidence between the two interfering laser beams (θ) via λ_{DLIP} = λ/[2sin(θ/2)], confined in micrometer-sized DLIP pixels that can be individually addressed and scanned across the surface (see Figure 5b). The minimum spatial period of the interference pattern is then given by λ_{DLIP} = λ/2. This restriction imposed by the optical diffraction limit can be overcome for LIPSS when HSFL structures are processed. The latter can exhibit spatial periods of only some tenths of the laser wavelength [1,5]. LSFL spatial periods, however, typically range between λ and λ/2 [1,5].
The depth of the DLIP ablation pattern can be independently controlled from its period by a proper choice of the laser pulse energy (fluence) and the number of pulses applied per pixel. In contrast, for LIPSS processing, the spatial period and the depth of the LIPSS also crucially depend on the fluence and the number of pulses per spot area, but both parameters usually cannot be controlled independently. For LIPSS, the surface modulation depth is typically limited at ~400 nm for LSFL and ~1000 nm for HSFL (dielectrics), depending on the materials and formation mechanisms. DLIP structures can have significantly larger modulation depths and higher regularities of periodic surface patterns, as demonstrated in Figure 6. The larger modulation depths may be beneficial for the tribological performance of the laser-structured surfaces [47] as they allow to better confine some lubricant in the tribological contact area [49].

The differences in the topographic characteristics also affect the optical properties of the (quasi-)periodic surface structures that may be used for safety tags, information encoding, and decoration purposes. The latter is based on the fact that surface grating structures can cause spectral and angular dependent diffraction of light, resulting in colorization effects of the treated samples. Figure 7 shows a photograph of a steel plate that was textured with similar grating-like DLIP structures and LIPSS (spatial periods ~1 µm) upon illumination with a point-like white light source [50]. The LIPSS patterned surface areas show a homogeneous colorization and a rather matte appearance, while the DLIP-treated regions exhibit brighter colors and a glossy appearance. Furthermore, the angular spectrum of the diffracted light is narrower in the case of the DLIP gratings when compared to the LIPSS. All these aspects finally point back to the different regularity of the surface structures, including deviations from the perfect grating geometry along with differences in their range of spatial periods.

Figure 5. (a) DLIP interference pattern generated by two laser beams overlapping at an angle $\theta$. (b) Scanning processing by displacement of multiple DLIP pixels. $p$: pulse (spot) separation, $h$: hatch distance; $d_p$: DLIP pixel size; $\Lambda$: DLIP spatial period. The direction of scanning is vertical here. Reprinted from Mezera et al. [48], Hierarchical Micro-/Nano-Structures on Polycarbonate via UV Pulsed Laser Processing, Nanomaterials, 2020, 10, 1184. Copyright 2020 under Creative Commons BY 4.0 license. Retrieved from https://doi.org/10.3390/nano10061184.
pulse durations in the ps-range or longer. Table 5 compiles a direct comparison of surface texturing
pulses and its impact on the resulting interference patterns, the DLIP technique is usually limited to
combine the benefits of both approaches on the costs of an additional processing step.

The corresponding atomic force microscopy (AFM) cross-section (b) indicates a depth modulation
profile. Structures processed by DLIP reveal a larger regularity in the SEM micrograph (c) and larger
depth modulations in the AFM cross-section (d). Adapted from Rung et al. [47], Possibilities of Dry
and Lubricated Friction Modification Enabled by Different Ultrashort Laser-Based Surface Structuring
Methods, Lubricants, 2019, 7, 43. Copyright 2019 under Creative Commons BY 4.0 license. Retrieved from
https://doi.org/10.3390/lubricants7050043.

Figure 7. Photograph of structural colors generated on a polished steel plate by DLIP and LIPSS
processing, as indicated on the sample. Reproduced from Soldera et al. [50], with permission from
Japan Laser Processing Society.
Employing up-to-date laser and beam scanning technology, the LIPSS processing approach and the DLIP technique both can fulfill current industrial demands by processing patterns at processing rates approaching the m²/min level [51–54]. Both surface patterning methods strongly depend on the coherence of the laser radiation used. The constraints, however, are somewhat different: while the contrast of the interference pattern generated in the DLIP pixel relies on global coherence (spatial and temporal), in LIPSS processing, only a local coherence of the beam is required, coupling the laser radiation to the material via scattering/interference at microscopic surface defects (roughness, absorption centers, etc.). Moreover, given the inherently large spectral bandwidth of ultrashort laser pulses and its impact on the resulting interference patterns, the DLIP technique is usually limited to pulse durations in the ps-range or longer. Table 5 compiles a direct comparison of surface texturing by DLIP or by LIPSS, summarizing the discussed aspects.

Table 5. Comparison of single beam surface processing of LIPSS with two-beam based DLIP structures.

| Property                        | DLIP (Two Beams) | LIPSS (One Beam) |
|---------------------------------|------------------|------------------|
| Spatial period                  | >λ/2 \(^1\)      | ~λ/10 (HSFL) – ~λ (LSFL) |
| Modulation depth [nm]           | 0–2000 [47]      | <1000 (HSFL) [5]  |
| Regularity of grating           | ++ \(^2\)        | +/−/\(\alpha\) 4 |
| Flexibility of processing       | pixelwise during scanning | continuous scanning |
| Control of periods/deptths      | ++ 2, independent | α 4, dependent |
| Complexity of setup             | ++ 2/+3          | 5 |
| Areal processing rate (current state) | <m²/min    | <1.5 m²/min [54] |
| Required beam coherence         | global           | local            |
| Pulse duration                  | ps-cw            | fs-cw            |

\(^1\) λ: laser irradiation wavelength. \(^2\): very good/very high. \(^3\): good/high. \(^4\): medium. \(^5\): low.

Recently, some groups started to investigate the hybrid processing of hierarchical surface structures of micrometric DLIP structures superimposed with nanometric LIPSS [48,55,56], which can combine the benefits of both approaches on the costs of an additional processing step.

3.4. Exploration of Other Applications

Other applications and of LIPSS that are currently explored are:

- Biomimetic surfaces: Nature provides many highly optimized surface functionalities that may be transferred to technical applications via tailored laser-processing, including LIPSS. Examples are dirt-repellent surfaces through the well-known lotus effect, anti-icing [57,58], the directional transport of liquids inspired by moisture-harvesting lizards [59] and bark bugs [60], antiadhesive surfaces inspired by cribellating spiders [61], or antibacterial [62–67], cell-repellent [68], and cell-stimulating/adapting surfaces [69–71] for medical applications [72]. A detailed review of the laser engineering of biomimetic surfaces is provided in [6].

- Combined processing strategies: Currently, several research groups are exploring the combination of LIPSS with additional surface treatment techniques—either “in situ” during the laser processing, or “ex situ” after the laser-processing. Examples are: (i) combined laser processing strategies (such as in situ double-pulse treatments [20,73,74] or ex situ LIPSS + DLIP, see Section 3.3), or a two-step laser processing of microstructures (e.g., lines, grids, or more complex microfluidic channels) patterned additionally with nanostructures (LIPSS) [59,75]; (ii) the combination of LIPSS processing with thermal heat during [76,77] or after [78,79] laser irradiation; (iii) electrochemical post-processing, such as anodization [67,80]; or (iv) ion beam post-processing for altering the electrical conductivity [81].

- Improved regularity of LIPSS through surface overlayers: On dielectrics, the generation of large surface areas covered homogeneously with LIPSS is often very difficult when the single photon energy is significantly smaller than the band gap energy, i.e., when nonlinear absorption is required.
to couple the laser beam energy with the solid. Apart from the strategy to reduce the nonlinearity via the irradiation wavelength [82], another way to overcome this difficulty can lie in adding a very thin strongly-absorbing surface overlayer on the dielectric in order to facilitate resonant coupling effects of the laser radiation to the material underneath. For hexagonally arranged ablative nanobumps on glass, tens of nanometer thick copper and silver coatings were shown to be suitable [83,84]. Later, Kunz et al. demonstrated that large surface areas homogeneously covered by HSFL can be processed on fused silica by the help of an additional 20 nm-thick gold layer [85].

- **LIPSS on thin films:** Often, the selective structuring of thin film coatings is necessary for creating specific surface functionalities. Conventional surface structuring techniques are, however, often limited by small film thicknesses in the sub-micrometer range and high hardness or brittleness of the film materials. Hence, several groups are exploring the (contactless) formation of LIPSS on various overlayer materials [86,87]. Furthermore, following the general trend of research on graphene (triggered by the Nobel prize awarded in 2010), several authors studied the formation of LIPSS on graphene or graphene oxide-covered substrates [88–92]. It was demonstrated that LIPSS manifesting via structural modifications of the graphene or the material underneath can be used as local probe of plasmonic resonances [91,92].

- **LIPSS for sensing applications:** One of the first applications of LIPSS came up in the context of black silicon that can be generated upon ultrashort laser processing of silicon as hierarchical surface morphology consisting of micrometric Spikes [93] covered with nanometric LIPSS. It was recognized by Mazur and his co-workers at Harvard University (USA) that these surface structures can be used for building silicon-based photodetector devices with an enhanced optical sensitivity in the (near) infrared spectral region. Later, this idea was commercialized and is already being used for night vision cameras [94]. Another sensing application of LIPSS used in chemical analytics is based on surface-enhanced Raman spectroscopy (SERS). The effect is based on electromagnetic near-field enhancement in the vicinity of very sharp surface topographic features and may be further enlarged by resonant effects, such as the excitation of SPPs. It was demonstrated that the SERS effect on LIPSS on polymers that were overcoated with gold can increase the detection sensitivity of specific analyte molecules by several orders of magnitude [95,96]. Additionally, the localized laser surface processing could help to spatially confine the analyte solution during an additional evaporation-based concentration enhancement step [97,98].

- **Magnetic and superconducting properties of LIPSS:** Several authors started to investigate the impact of LIPSS on magnetic [99–101] and superconducting properties [102].

### 3.5. Funding Strategies for LIPSS: The European H2020 Perspective

The European Commission (EC) supports the research on LIPSS currently via their Horizon 2020 (H2020) programme. Table 6 lists some corresponding projects that are funded through different schemes. Those H2020 funding opportunities are briefly discussed in the following section.

Laserlab-Europe is a consortium of currently ~30 major laser research infrastructures, located in 18 European countries ([https://www.laserlab-europe.eu](https://www.laserlab-europe.eu)). The network has been in development since 2004 and provides access to their laser facilities to a broad user community, pursues research and development for improved access and research opportunities, and aims to foster networking activities for strengthening the European laser research landscape. Currently, it is supported by the EC in the Integrating Activities for Advanced Communities programme, as a part of the Research and Innovation Action (RIA) scheme.
Table 6. Research projects on LIPSS funded by the European Commission (EC) within the Horizon 2020 (H2020) programme.

| Acronym          | Name                                                                                                                                  | Duration       | Website                                                                 |
|------------------|---------------------------------------------------------------------------------------------------------------------------------------|----------------|------------------------------------------------------------------------|
| LASERLAB-EUROPE  | The Integrated Initiative of European Laser Research Infrastructures as Laser-induced Nanostructures as                                | 2019–2023      | https://cordis.europa.eu/project/id/871124                              |
| LiNaBioFluid     | Biomimetic Model of Fluid Transport in the Integument of Animals                                                                      | 2015–2018      | https://cordis.europa.eu/project/id/665337                              |
| Laser4Fun        | European ESRs 1 Network on short pulsed laser Micro/Nanostructuring of Surfaces High throughput laser texturing of self-cleaning and antibacterial surfaces | 2015–2019      | https://cordis.europa.eu/project/id/675063/                             |
| TresClean        | Laser for mass production of functionalized metallic surfaces                                                                         | 2016–2020      | https://cordis.europa.eu/project/id/687613/                             |
| LASER4SURF       | Laser-free Ti-based Medical Implants due to Laser-induced Microstructures                                                             | 2018–2019      | https://cordis.europa.eu/project/id/800852/                             |
| CellFreeImplant  | Cell-free Laser Bionic Surfaces                                                                                                       | 2018–2020      | https://cordis.europa.eu/project/id/801250/                             |
| LaBionicS        | High throughput Laser structuring with Multiscale Periodic feature sizes for Advanced Surface Functionalities                           | 2019–2021      | https://cordis.europa.eu/project/id/825132/                             |
| LAMPAS           | Functional surface treatments using ultra-short pulse laser system                                                                     | 2019–2021      | https://cordis.europa.eu/project/id/825151/                             |
| FemtoSurf        | Bio-inspired Protection of Marble with Lasers                                                                                         | 2019–2021      | https://cordis.europa.eu/project/id/852048/                             |
| BioProMarL       | Antiadhesive Bionic Combs for Handling of Nanofibers Laser-induced hierarchical                                                         | 2019–2022      | https://cordis.europa.eu/project/id/862016/                             |
| BioCombs4-Nanofibers | micro-/nano-structures for controlled cell adhesion at implants                                                                     | 2021–2022      | https://cordis.europa.eu/project/id/951730/                             |

1 Early stage researchers.

Within the same RIA scheme, EC also supports Future and Emerging Technologies (FET), e.g., in the frame of FET Open projects (e.g., LiNaBioFluid, BioCombs4Nanofibers), FET Proactive projects (e.g., LaserImplant), or smaller Coordination and Support Actions (e.g., CellFreeImplant, LaBionicS, BioProMarL). Such interdisciplinary projects develop early-stage science and technology research exploring new foundations for radically new future technologies and should provide a long-term vision of high-risk research.

Other LIPSS projects are supported within the RIA scheme by the Industrial Leadership programme (e.g., TresClean, LAMPAS, FemtoSurf) or the Technologies for Factories of the Future programme (e.g., LASER4SURF). Fostering new skills by means of excellent initial training of early-stage researchers is provided through Marie Skłodowska-Curie Innovative Training Networks (e.g., Laser4Fun).

In 2019, the EC’s European Innovation Council Pathfinder started an initiative for the dissemination and exploitation of results obtained within FET projects through the Future Tech Week (http://futuretechweek.fetfx.eu/).

4. Future Trends and Open Questions

Through ultrafast time-resolved experiments and the development of advanced numerical simulations combining electromagnetic and matter reorganization theories, a unified view on LIPSS is currently being developed. While the role of the electromagnetic scattering in LIPSS formation is already widely clarified, there is still an ongoing debate on the matter reorganization side, whether the Marangoni instability or the Rayleigh–Taylor instability provide dominant contributions in the hydrodynamic relaxation stage that is following the optical material excitation.

Moreover, an ongoing interest in LIPSS for practical applications is observed, e.g., for developing tailored surface functionalities. Current areal LIPSS processing rates are at the m² min⁻¹ level. It can be expected that future developments in laser technology enabling pulse repetition frequencies in the GHz range and modern laser scanner technology, along with smart scanning strategies for managing
and optimizing the residual thermal load imposed to the laser irradiated material, will allow industrial processing rates at the m² s⁻¹ level. This will also further reduce the costs of LIPSS processing that were estimated to be ~0.05 €/cm² in 2019 [3].

While most of the research on LIPSS was driven and interpreted on the basis of physical effects and models, it becomes clear, in practice, that additional effects involving the local surface chemistry and the environment must be considered and properly controlled for industrial or medical applications, e.g., for surface wetting, adhesion, implant functionalization, etc. It can be expected that the role of chemical effects accompanying the formation of LIPSS will represent an important future trend of research on LIPSS. The combination of MD and FDTD simulations may allow new future insights here. Moreover, in the context of numerical simulations, machine learning algorithms can enable the predictive modeling of optimized laser processing parameters for the desired surface topography [103].

Another future trend will be in the continued exploration of already-established and new surface functionalities that can be created through LIPSS. One particular aspect may be the long-term stabilization of the surface wetting characteristics (e.g., hydrophobicity or -philicity) of LIPSS in real-life environments and in daily use. In this context, the author expects that the remarkable number of research projects funded by the European Commission (see Section 3.5) will result in new and improved industrial applications in fields of mechanical engineering, healthcare, aviation, shipping, jewelry, or for consumer goods.

**Funding:** The author acknowledges the projects LiNaBioFluid, CellFreeImplant, BioCombs4Nanofibers, and LaserImplant. These projects have received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreements No. 665337 (LiNaBioFluid, No. 800832 (CellFreeImplant), No. 862016 (BioCombs4Nanofibers, https://www.jku.at/biocombs4nanofibers), and No. 951730 (LaserImplant).

**Acknowledgments:** This article intends to stimulate further research and development in the field of LIPSS and to support the Future Tech Week 2020, an initiative of the European Innovation Council Pathfinder, http://futuretechweek.fetfx.eu/.

**Conflicts of Interest:** The author declares no conflict of interest.

**References**

1. Bonse, J.; Höhm, S.; Kirner, S.V.; Rosenfeld, A.; Krüger, J. Laser-induced periodic surface structures—A scientific evergreen. IEEE J. Sel. Top. Quantum Electron. 2017, 23, 9000615. [CrossRef]

2. Vorobyev, A.Y.; Guo, C. Direct femtosecond laser surface nano/microstructuring and its applications. Laser Photonics Rev. 2013, 7, 385–407. [CrossRef]

3. Florian, C.; Kirner, S.V.; Krüger, J.; Bonse, J. Surface functionalization by laser-induced periodic surface structures. J. Laser Appl. 2020, 32, 022063. [CrossRef]

4. Gräf, S. Formation of laser-induced periodic surface structures on different materials: Fundamentals, properties and applications. Adv. Opt. Technol. 2020, 9, 11–39. [CrossRef]

5. Bonse, J.; Kirner, S.V.; Krüger, J. Laser-Induced Periodic Surface Structures (LIPSS). In Handbook of Laser Micro- and Nano-Engineering; Sugiotto, K., Ed.; Springer: Cham, Switzerland, 2020.

6. Stratakis, E.; Bonse, J.; Heitz, J.; Siegel, J.; Tsibidis, G.D.; Skoulas, E.; Papadopoulos, A.; Mimidis, A.; Joel, A.C.; Comanns, P.; et al. Laser engineering of biomimetic surfaces. Mater. Sci. Eng. R 2020, 141, 100562. [CrossRef]

7. Ahmmed, K.M.T.; Gembrub, C.; Kietzig, A.-M. Fabrication of micro/nano structures on metals by femtosecond laser micromachining. Micromachines 2014, 5, 1219. [CrossRef]

8. Rudenko, A.; Colombier, J.-P.; Höhm, S.; Rosenfeld, A.; Krüger, J.; Bonse, J.; Itina, T.E. Spontaneous periodic ordering on the surface and in the bulk of dielectrics irradiated by ultrafast laser: A shared electromagnetic origin. Sci. Rep. 2017, 7, 12306. [CrossRef]

9. Kirner, S.V.; Wirth, T.; Sturm, H.; Krüger, J.; Bonse, J. Nanometer-resolved chemical analyses of femtosecond laser-induced periodic surface structures on titanium. J. Appl. Phys. 2017, 122, 10490. [CrossRef]

10. van Driel, H.M.; Sipe, J.E.; Young, J.F. Laser-induced periodic surface structures on solids: A universal phenomenon. Phys. Rev. Lett. 1982, 49, 1955–1958. [CrossRef]

11. Sipe, J.E.; Young, J.F.; Preston, J.S.; van Driel, H.M. Laser-induced periodic surface structure. I. Theory. Phys. Rev. B 1983, 27, 1141–1154. [CrossRef]
12. Young, J.F.; Preston, J.S.; van Driel, H.M.; Sipe, J.E. Laser-induced periodic surface structure. II. Experiments on Ge, Si, Al, and brass. Phys. Rev. B 1983, 27, 1155–1172. [CrossRef]

13. Young, J.F.; Sipe, J.E.; van Driel, H.M. Laser-induced periodic surface structure. III. Fluence regimes, the role of feedback, and details of the induced topography in germanium. Phys. Rev. B 1984, 30, 2001–2015. [CrossRef]

14. Guo, Z.; Fauchet, P.M.; Siegman, A. Growth of spontaneous periodic surface structures on solids during laser illumination. Phys. Rev. B 1982, 26, 5366–5381. [CrossRef]

15. Fauchet, P.M.; Siegman, A. Surface ripples on silicon and gallium arsenide under picosecond laser illumination. Appl. Phys. Lett. 1982, 40, 824–826. [CrossRef]

16. van Driel, H.M.; Sipe, J.E.; Young, J.F. Laser-induced coherent modulation of solid and liquid surfaces. J. Lumin. 1985, 30, 446–471. [CrossRef]

17. Siegman, A.E.; Fauchet, P.M. Stimulated Wood’s anomaly on laser-illuminated surfaces. IEEE J. Quantum Electron. 1986, 22, 1384–1403. [CrossRef]

18. Akhmanov, S.A.; Emel’yanov, V.I.; Koroteev, N.I.; Seminogov, V.N. Interaction of powerful laser radiation with the surfaces of semiconductors and metals: Nonlinear optical effects and nonlinear optical diagnostics. Sov. Phys. Usp. 1985, 28, 1084–1124. [CrossRef]

19. Bonch-Bruevich, A.M.; Libenson, M.N.; Makin, V.S.; Trubaev, V.V. Surface electromagnetic waves in Optics. Opt. Eng. 1992, 31, 718–730. [CrossRef]

20. Höhm, S.; Herzlieb, M.; Rosenfeld, A.; Krüger, J.; Bonse, J. Dynamics of the formation of laser-induced periodic surface structures (LIPSS) upon femtosecond two-color double-pulse irradiation of metals, semiconductors, and dielectrics. Appl. Surf. Sci. 2016, 374, 331–338. [CrossRef]

21. Sokolowski-Tinten, K.; Barty, A.; Boutet, S.; Shymonovich, U.; Chapman, H.; Bogan, M.; Marchesini, S.; Hau-Riege, S.; Stojanovic, N.; Bonse, J.; et al. Short-pulse laser induced transient structure formation and ablation studied with time-resolved coherent XUV-scattering. AIP Conf. Proc. 2010, 1278, 373–379.

22. Bonse, J. Scattering on scattering. Light Sci. Appl. 2017, 6, e17088. [CrossRef] [PubMed]

23. Höhm, S.; Rosenfeld, A.; Krüger, J.; Bonse, J. Femtosecond diffraction dynamics of laser-induced periodic surface structures on fused silica. Appl. Phys. Lett. 2013, 102, 054102. [CrossRef]

24. García-Lechuga, M.; Puerto, D.; Fuentes-Edsfu, Y.; Solis, J.; Siegel, J. Ultrafast moving-spot microscopy: Birth and growth of laser-induced periodic surface structures. ACS Photonics 2016, 3, 1961–1967. [CrossRef]

25. Her, T.-H. Femtosecond-Laser-Induced Periodic Self-Organized Nanostructures. In Comprehensive Nanoscience and Technology: Nanofabrication and Devices; Andrews, D., Scholes, G., Wiederrecht, G., Eds.; Academic Press: New York, NY, USA, 2011; Volume 4, pp. 277–314.

26. Buividis, R.; Mikutis, M.; Juodkazis, S. Surface and bulk structuring of materials by ripples with long and short laser pulses: Recent advances. Prog. Quantum Electron. 2014, 38, 119–156. [CrossRef]

27. Shimotsuma, Y.; Kazanski, P.G.; Qiu, J.; Hirao, K. Self-organized nanogratings in glass irradiated by ultrashort light pulses. Phys. Rev. Lett. 2003, 91, 247405. [CrossRef] [PubMed]

28. Bonse, J.; Gräf, S. Maxwell meets Marangoni—A review of theories on laser-induced periodic surface structures. Laser Photonics Rev. 2020, 14, 2000215. [CrossRef]

29. Rudenko, A.; Abou-Saleh, A.; Pigeon, F.; Mauclair, C.; Garrelie, F.; Stoian, R.; Colombier, J.-P. High-frequency periodic patterns driven by non-radiative fields coupled with Marangoni convection instabilities on laser-excited metal surfaces. Acta Mater. 2020, 194, 93–105. [CrossRef]

30. Müller, F.A.; Kunz, C.; Gräf, S. Bio-inspired functional surfaces based on laser-induced periodic surface structures. Materials 2016, 9, 476. [CrossRef]

31. Skolski, J.Z.P.; Römer, G.R.B.E.; Obona, J.V.; Ocelik, V.; Huis in ’t Veld, A.J.; de Hosson, J.T.M. Laser-induced periodic surface structures: Fingerprints of light localization. Phys. Rev. B 2012, 85, 075320. [CrossRef]

32. Zhang, H.; Colombier, J.-P.; Faure, N.; Cheng, G.; Stoian, R. Coherence in ultrafast laser-induced periodic surface structures. Phys. Rev. B 2015, 92, 174109. [CrossRef]

33. Tsibidis, G.D.; Barberoglou, M.; Loukakos, P.A.; Stratakis, E.; Fotakis, C. Dynamics of ripple formation on silicon surfaces by ultrashort laser pulses in subablation conditions. Phys. Rev. B 2012, 86, 115316. [CrossRef]

34. Ivanov, D.S.; Lipp, V.P.; Blumenstein, A.; Kleinwort, F.; Veiko, V.P.; Yakovlev, E.; Röddatis, V.; Garcia, M.E.; Rethfeld, B.; Ihlemann, J.; et al. Experimental and theoretical investigation of periodic nanostructuring of Au with ultrashort UV laser pulses near the damage threshold. Phys. Rev. Appl. 2015, 4, 064006. [CrossRef]

35. Shugaev, M.V.; Gnilitskyi, I.; Bulgakova, N.M.; Zhigilei, L.V. Mechanism of single-pulse ablative generation of laser-induced periodic surface structures. Phys. Rev. B 2017, 96, 205429. [CrossRef]
36. Landis, E.C.; Phillips, K.C.; Mazur, E.; Friend, C.M. Formation of nanostructured TiO$_2$ by femtosecond laser irradiation of titanium in O$_2$. *J. Appl. Phys.* 2012, 112, 063108. [CrossRef]

37. Öktem, B.; Pavlov, I.; Ilday, S.; Kalayçoğlu, H.; Rybak, A.; Yavaş, S.; Erdoğan, M.; Ilday, F.O. Nonlinear laser lithography for indefinitely large-area nanostructuring with femtosecond pulses. *Nat. Photonics* 2013, 7, 897–901. [CrossRef]

38. Dostovalov, A.V.; Korolok, V.P.; Okotrub, K.A.; Bronnikov, K.A.; Babin, S.A. Oxide composition and period variation of thermochemical LIPSS on chromium films with different thickness. *Opt. Express* 2018, 26, 7712–7723. [CrossRef]

39. Florian, C.; Déziel, J.L.; Kirner, S.V.; Siegel, J.; Bonse, J. The role of the laser-induced oxide layer in the formation of laser-induced periodic surface structures. *Nanomaterials* 2020, 10, 147. [CrossRef]

40. Zwahr, C.; Welle, A.; Weingärtner, T.; Heinemann, C.; Kruppke, B.; Gulow, N.; Holthaus, M.G.; Lasagni, A.F. Ultrashort pulsed laser surface patterning of titanium to improve osseointegration of dental implants. *Adv. Eng. Mater.* 2019, 21, 1900639. [CrossRef]

41. Florian, C.; Wonneberger, R.; Undisz, A.; Kirner, S.V.; Wasmuth, K.; Spaltmann, D.; Krüger, J.; Bonse, J. Chemical effects during the formation of various types of femtosecond laser-generated surface structures on titanium alloy. *Appl. Phys. A* 2020, 126, 266. [CrossRef]

42. Kirner, S.V.; Slachciak, N.; Elert, A.M.; Griepentrog, M.; Fischer, D.; Hertwig, A.; Sahre, M.; Dörfel, I.; Sturm, H.; Pentzien, S.; et al. Tribological performance of titanium samples oxidized by fs-laser radiation, thermal heating, or electrochemical anodization. *Appl. Phys. A* 2018, 124, 326. [CrossRef]

43. Ayerdí, J.J.; Slachciak, N.; Llavori, I.; Zubala, A.; Aginagalde, A.; Bonse, J.; Spaltmann, D. On the role of a ZDDP in the tribological performance of femtosecond laser-induced periodic surface structures on titanium alloy against different counterbody materials. *Lubricants* 2019, 7, 79. [CrossRef]

44. Kietzig, A.M.; Hatzikiriakos, S.G.; Englezos, P. Patterned superhydrophobic metallic surfaces. *Langmuir* 2009, 25, 4821–4827. [CrossRef] [PubMed]

45. Yasumaru, N.; Sentoku, E.; Kiuchi, J. Formation of organic layer on femtosecond laser-induced periodic surface structures. *Appl. Surf. Sci.* 2017, 405, 267–272. [CrossRef]

46. Gregorčič, P. Comment on "Bioinspired reversible switch between underwater superoleophobicity/superaerophobicity and oleophilicity/aerophilicity and improved antireflective property on the nanosecond laser-ablated superhydrophobic titanium surfaces". *ACS Appl. Mater. Interfaces* 2020. [CrossRef] [PubMed]

47. Rung, S.; Bokan, K.; Kleinwort, F.; Schwarz, S.; Simon, P.; Klein-Wiele, J.-H.; Esen, C.; Hellmann, R. Possibilities of dry and lubricated friction modification enabled by different ultrashort laser-based surface structuring methods. *Lubricants* 2019, 7, 43. [CrossRef]

48. Mezera, M.; Alamri, S.; Hendriks, W.A.P.M.; Hertwig, A.; Elert, A.M.; Bonse, J.; Kunze, T.; Lasagni, A.F.; Römer, G.R.B.E. Hierarchical micro-/nano-structures on polycarbonate via UV pulsed laser processing. *Nanomaterials* 2020, 10, 1184. [CrossRef]

49. Bonse, J.; Kirner, S.V.; Griepentrog, M.; Spaltmann, D.; Krüger, J. Femtosecond laser texturing of surfaces for tribological applications. *Materials* 2018, 11, 801. [CrossRef]

50. Soldera, M.; Fortuna, F.; Teutoburg-Weiss, S.; Milles, S.; Taretto, K.; Lasagni, A.F. Comparison of structural colors achieved by laser-induced periodic surface structures and direct laser interference patterning. *J. Laser MicroNanoeng.* 2020, 15, 97–103.

51. Mincuzzi, M.; Gemini, L.; Faucon, M.; Kling, R. Extending ultra-short pulse laser texturing over large area. *Appl. Surf. Sci.* 2016, 386, 65–71. [CrossRef]

52. Lang, V.; Roch, T.; Lasagni, A.F. High-speed surface structuring of polycarbonate using direct laser interference patterning: Toward 1 m$^2$/min$^{-1}$ fabrication speed barrier. *Adv. Eng. Mater.* 2016, 18, 1342–1348. [CrossRef]

53. Faas, S.; Bielke, U.; Weber, R.; Graf, T. Scaling the productivity of laser structuring processes using picosecond laser pulses at average powers of up to 420 W to produce superhydrophobic surfaces on stainless steel AISI 316L. *Sci. Rep.* 2019, 9, 1933. [CrossRef] [PubMed]

54. Schille, J.; Schneider, L.; Mauersberger, S.; Szokup, S.; Höhn, S.; Pötschke, J.; Reiß, F.; Leidich, E.; Löschner, U. High-rate laser surface texturing for advanced tribological functionality. *Lubricants* 2020, 8, 33. [CrossRef]

55. Alamri, S.; Fragigelakis, F.; Kunze, T.; Krupop, B.; Mincuzzi, G.; Kling, R.; Lasagni, A.F. On the interplay of DLIP and LIPSS upon ultra-short laser pulse irradiation. *Materials* 2019, 12, 1018. [CrossRef] [PubMed]

56. Ehrhardt, M.; Lai, S.; Lorenz, P.; Zimmer, K. Guiding of LIPSS formation by excimer laser irradiation of pre-patterned polymer films for tailored hierarchical structures. *Appl. Surf. Sci.* 2020, 506, 144785. [CrossRef]
57. Römer, G.; del Cerro, D.A.; Sipkema, R.C.J.; Groenendijk, M.N.W.; Huis in’t Veld, A.J. Ultra short pulse laser generated surface textures for anti-ice applications in aviation. In Proceedings of the 28th International Congress on Applications of Lasers & Electro-Optics, ICALEO 2009, Orlando, FL, USA, 2–5 November 2009; Laser Institute of America: Orlando, FL, USA, 2009; pp. 30–37.

58. Vercillo, V.; Tonnicchia, S.; Romano, J.; García-Girón, A.; Aguilar-Morales, A.I.; Alamri, S.; Dimov, S.S.; Kunze, T.; Lasagni, A.F.; Bonaccurso, E. Design rules for laser-treated icephobic metallic surfaces for aeronautic applications. *Adv. Funct. Mater.* **2020**, *30*, 1910268. [CrossRef]

59. Hermens, U.; Kirner, S.V.; Emonts, C.; Comanns, P.; Skoulas, E.; Mimidis, A.; Mescheder, H.; Winands, K.; Krüger, J.; Stratakis, E.; et al. Mimicking lizard-like surface structures upon ultrashort laser pulse irradiation of inorganic materials. *Appl. Surf. Sci.* **2017**, *365*, 499–507. [CrossRef]

60. Kirner, S.V.; Hermens, U.; Mimidis, A.; Skoulas, E.; Florian, C.; Hischen, F.; Plamadeala, C.; Baumgartner, W.; Winands, K.; Mescheder, H.; et al. Mimicking bug-like surface structures and their fluid transport produced by ultrashort laser pulse irradiation of steel. *Appl. Phys. A* **2017**, *123*, 754. [CrossRef]

61. Joel, A.-C.; Meyer, M.; Heitz, J.; Heiss, A.; Park, D.; Adamova, H.; Baumgartner, W. Biomimetic combs as antiadhesive tools to manipulate nanofibers. *ACS Appl. Nano Mater.* **2020**, *3*, 3395–3401. [CrossRef]

62. Cunha, A.; Elie, A.-M.; Plawinski, L.; Serro, A.P.; Botelho do Rego, A.M.; Almeida, A.; Urdaci, M.C.; Durrieu, M.-C.; Vilar, R. Femtosecond laser surface texturing of titanium as a method to reduce the adhesion of Staphyloccocus aureus and biofilm formation. *Appl. Surf. Sci.* **2016**, *360*, 485–493. [CrossRef]

63. Epperlein, N.; Menzel, F.; Schwibbert, K.; Koter, R.; Bonse, J.; Sameith, J.; Krüger, J.; Toepel, J. Influence of femtosecond laser produced nanostructures on biofilm growth on steel. *Appl. Surf. Sci.* **2017**, *418*, 420–424. [CrossRef]

64. Schwibbert, K.; Menzel, F.; Epperlein, N.; Bonse, J.; Krüger, J. Bacterial adhesion on femtosecond laser-modified polyethylene. *Materials* **2019**, *12*, 3107. [CrossRef] [PubMed]

65. Slepička, P.; Siegel, J.; Lyutakov, O.; Slepičková Kasáčková, N.; Kolská, Z.; Bačáková, L.; Švorčík, V. Polymer nanostructures for bioapplications induced by laser treatment. *Biotechnol. Adv.* **2018**, *36*, 839–855. [CrossRef] [PubMed]

66. Neděla, O.; Slepička, P.; Slepičková Kasáčková, N.; Hajdl, P.; Kolská, Z.; Švorčík, V. Antibacterial properties of angle-dependent nanopatterns on polystyrene. *React. Funct. Polymer* **2019**, *136*, 173–180. [CrossRef]

67. Fajstavr, D.; Neznaľová, K.; Slepičková Kasáčková, N.; Rimpelová, S.; Kubičíková, K.; Švorčík, V.; Slepička, P. Nanostructured Polystyrene Doped with Acetylsalicylic Acid and Its Antibacterial Properties. *Materials* **2020**, *13*, 3609. [CrossRef]

68. Heitz, J.; Plamadeala, C.; Muck, M.; Armbruster, O.; Baumgartner, W.; Weth, A.; Steinwender, C.; Blessberger, H.; Kellermaier, J.; Kirner, S.V.; et al. Femtosecond laser-induced microstructures on Ti substrates for reduced cell adhesion. *Appl. Phys. A* **2017**, *123*, 734. [CrossRef]

69. Rebollar, E.; Pérez, S.; Hernández, M.; Domingo, C.; Martín, M.; Ezquerra, T.A.; García-Ruiz, J.P.; Castillo, M. Physicochemical modifications accompanying UV laser induced surface structures on poly(ethyleneterephthalate) and their effect on adhesion of mesenchymal cells. *Phys. Chem. Chem. Phys.* **2014**, *16*, 17551–17559. [CrossRef]

70. Barb, R.-A.; Hrelescu, C.; Dong, L.; Heitz, J.; Siegel, J.; Slepička, P.; Vosmanska, V.; Svorčík, V.; Magnus, B.; Marksteiner, R.; et al. Laser-induced periodic surface structures on polymers for formation of gold nanowires and activation of human cells. *Appl. Phys. A* **2014**, *117*, 295–300. [CrossRef]

71. Michaljaničová, I.; Slepička, P.; Rimpelová, S.; Slepičková Kasáčková, N.; Švorčík, V. Regular pattern formation on surface of aromatic polymers and its cytocompatibility. *Appl. Surf. Sci.* **2016**, *370*, 131–141. [CrossRef]

72. Fosodeder, P.; Baumgartner, W.; Steinwender, C.; Hassel, A.W.; Florian, C.; Bonse, J.; Heitz, J. Repellent rings at titanium cylinders against overgrowth by fibrobasts. *Adv. Opt. Technol.* **2020**, *9*, 113–120. [CrossRef]

73. Fraggelakis, F.; Mincuzzi, G.; Lopez, J.; Manek-Hönninger, I.; Kling, R. Controlling 2D laser nano structuring over large area with double femtosecond pulses. *Appl. Surf. Sci.* **2019**, *470*, 677–686. [CrossRef]

74. Jiang, L.; Wang, A.-D.; Li, B.; Cui, T.-H.; Lu, Y.-F. Electrons dynamics control by shaping femtosecond laser pulses in micro/nanofabrication: Modeling, method, measurement and application. *Light: Sci. Appl.* **2018**, *7*, 171134. [CrossRef]
Her, T.-H.; Finlay, R.J.; Wu, C.; Deliwala, S.; Mazur, E. Microstructuring of silicon with femtosecond laser pulses. *Appl. Surf. Sci.* 2016, 374, 81–89. [CrossRef]  

Deng, G.; Feng, G.; Zhou, S. Experimental and FDTD study of silicon surface morphology induced by femtosecond laser irradiation at a high substrate temperature. *Opt. Express* 2017, 25, 7818–7827. [CrossRef] [PubMed]  

Gráf, S.; Kunz, C.; Engel, S.; Derrien, T.-J.-Y.; Müller, F.A. Femtosecond laser-induced periodic surface structures on fused silica: The impact of the initial substrate temperature. *Materials* 2018, 11, 1340. [CrossRef] [PubMed]  

Fan, P.; Zhong, M. Laser Surface Micro-Nano Structuring via Hybrid Process. In *Handbook of Laser Micro- and Nano-Engineering*; Sugio, K., Ed.; Springer: Cham, Switzerland, 2020.  

Sotillo, B.; Ariza, R.; Siegel, J.; Solís, J.; Fernandez, P. Preferential growth of ZnO micro- and nanostructure assemblies on fs-laser-induced periodic structures. *Nanomaterials* 2020, 10, 731. [CrossRef] [PubMed]  

Lone, S.A.; Muck, M.; Fosodeder, P.; Mardare, C.C.; Florian, C.; Weth, A.; Krüger, J.; Steinwender, C.; Baumgartner, W.; Heitz, J.; et al. Impact of femtosecond laser treatment accompanied with anodization of titanium alloy on fibroblast cell growth. *Phys. Stat. Sol. (a)* 2020, 217, 1900838. [CrossRef]  

Yang, H.Z.; Wang, W.J.; Jiang, G.D.; Mei, X.S.; Pan, A.F.; Chen, T. Nanostructures with good photoelectric properties fabricated by femtosecond laser and secondary sputtering on ITO films. *Opt. Mater.* 2020, 109, 110302. [CrossRef]  

Martínez-Calderón, M.; Azkona, J.J.; Casquero, N.; Rodriguez, A.; Domke, M.; Gómez-Aranzadi, M.; Olaizola, S.M.; Granados, E. Tailoring diamond’s optical properties via direct femtosecond laser nanostructuring. *Sci. Rep.* 2018, 8, 14262. [CrossRef]  

He, Y.; Zhang, J.; Singh, S.; Garcell, E.; Vorobyev, A.Y.; Lam, B.; Zhan, Z.; Yang, J.; Guo, C. Maskless laser nano-lithography of glass through sequential activation of multi-threshold ablation. *Appl. Phys. Lett.* 2019, 114, 133107. [CrossRef]  

Zou, T.; Zhao, B.; Xin, W.; Wang, Y.; Wang, B.; Zheng, X.; Xie, H.; Zhang, Z.; Yang, J.; Guo, C. High-speed femtosecond laser plasmonic lithography and reduction of graphene oxide for anisotropic photosresponse. *Light Sci. Appl.* 2020, 9, 69. [CrossRef]  

Dragowska-Horna, K.A.; Mirza, I.; Rodriguez, A.; Kovaříček, P.; Sládek, J.; Derrien, T.J.-Y.; Gedvilaš, M.; Račiukaitis, G.; Frank, O.; Bulgakova, N.M.; et al. Periodic surface functional group density on graphene via laser-induced substrate patterning at Si/SiO2 interface. *Nano Res.* 2020, 13, 2323–2339. [CrossRef]  

Crawford, M. Black Silicon: 23 Years Later. *SPIE Prof.* 2019, 14, 26–29.
95. Rebollar, E.; Sanz, M.; Pérez, S.; Hernández, M.; Martin-Fabiani, I.; Rueda, D.R.; Ezquerra, T.A.; Domingo, C.; Castillejo, M. Gold coatings on polymer laser induced periodic surface structures: Assessment as substrates for surface-enhanced Raman scattering. *Phys. Chem. Chem. Phys.* **2012**, *14*, 15699–15705. [CrossRef] [PubMed]

96. Rebollar, E.; Castillejo, M.; Ezquerra, T.A. Laser Induced Periodic Surface Structures on Polymer Films: From Fundamentals to Applications. *Eur. Polym. J.* **2015**, *73*, 162–174. [CrossRef]

97. Pavliuk, G.; Pavlov, D.; Mitsai, E.; Vitrik, O.; Mironenko, A.; Zakharenko, A.; Kulinich, S.; Juodkazis, S.; Bratskaya, S.; Zhizhchenko, A. Ultrasensitive SERS-Based Plasmonic Sensor with Analyte Enrichment System Produced by Direct Laser Writing. *Nanomaterials* **2019**, *10*, 49. [CrossRef] [PubMed]

98. Hu, X.; Pan, R.; Cai, M.; Liu, W.; Luo, X.; Chen, C.; Jiang, G.; Zhong, M. Ultrafast laser micro-nano structured superhydrophobic teflon surfaces for enhanced SERS detection via evaporation concentration. *Adv. Opt. Technol.* **2020**, *9*, 89–100. [CrossRef]

99. Czajkowski, K.; Ratzke, M.; Varlamova, O.; Reif, J. Femtosecond-laser-induced periodic surface structures on magnetic layer targets: The roles of femtosecond-laser interaction and of magnetization. *Appl. Surf. Sci.* **2017**, *418*, 84–87. [CrossRef]

100. Arranz, M.A.; Sánchez, E.H.; Rebollar, E.; Castillejo, M.; Colino, J.M. Form and magnetic birefringence in undulated permalloy/PET films. *Opt. Express* **2019**, *27*, 21285–21294. [CrossRef]

101. Sánchez, E.H.; Rodríguez-Rodríguez, G.; Aragón, R.; Arranz, M.A.; Rebollar, E.; Castillejo, M.; Colino, J.M. Anisotropy engineering of soft thin films in the undulated magnetic state. *J. Magn. Magn. Mater.* **2020**, *514*, 167149. [CrossRef]

102. Cubero, A.; Martínez, E.; Angurel, L.A.; de la Fuente, G.F.; Navarro, R.; Legall, H.; Krüger, J.; Bonse, J. Effects of laser-induced periodic surface structures on the superconducting properties of niobium. *Appl. Surf. Sci.* **2020**, *508*, 145140. [CrossRef]

103. Velli, M.-C.; Tsibidis, G.D.; Mimidis, A.; Skoulas, E.; Pantazis, V.; Stratakis, E. Predictive modeling approaches in laser-based material processing. *arXiv* **2020**, arXiv:2006.07686. Available online: https://arxiv.org/abs/2006.07686 (accessed on 23 September 2020).