Tutorial

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Femtosecond lasers: the ultimate tool for high-precision 3D manufacturing

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Abstract: The ever-growing trend of device multifunctionality and miniaturization puts enormous burden on existing manufacturing technologies. The requirements for precision, throughput, and cost become increasingly harder to achieve with minimal room for compromises. Femtosecond lasers, which saw immense development throughout the last few decades, have been proven time and time again to be a superb tool capable of standing up to the challenges posed by modern science and the industry for ultrahigh-precision material processing. Thus, this paper is dedicated to provide an outlook on how femtosecond pulses are revolutionizing modern manufacturing. We will show how they are exploited for various kinds of material processing, including subtractive (ablation, cutting, and etching), additive (lithography and laser-induced forward transfer), or hybrid subtractive-additive cases. The advantages of using femtosecond lasers in such applications, with main focus on how they enable the most precise kinds of material processing, will be highlighted. Future prospects concerning emerging industrial applications and the future of the technology itself will be discussed.

Keywords: 3D nanolithography; direct laser writing; femtosecond lasers; material processing; ultrafast phenomena.

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1 Introduction

Ever since the beginning of human history, entire eras have been defined according to the main technological advancement: Bronze Age, Iron Age, Industrial Revolution, etc. In the wake of the 21st century, the Fourth Industrial Revolution is in its full swing, blurring the lines between classical science and engineering fields [1]. As a result, an entirely new generation of functional device concepts emerged, combining the newest advances in cybernetics, biology, nanotechnologies, and other similar fields. However, to transfer such concepts from idea to reality, a completely new outlook to modern manufacturing techniques is required. They have to be precise down to the nanometer scale, offer easy on-demand tunability between various designs that need to be manufactured, and finally have throughput and cost ratio suitable for mass production. For this reason, new ways to produce functional devices are being investigated, ranging from self-organization [2, 3] to ultra-advanced 3D printing [4, 5].

Laser-based solutions stand out among other material processing techniques as being incredibly versatile and easy to adopt for most given applications. Indeed, it took just a few years from the creation of the first operational laser to full-on investigations of advanced nonlinear light-matter interactions. Heavy industry was fast to grasp the potential of lasers as simple, relatively cheap, fast, and contact-less tools for manufacturing, adopting them into macromanufacturing where they are unmatched up until this day. However, most of these lasers are either continuous wave or operating at long pulse duration (millisecond to nanosecond) with submillimeter processing quality. Although this is completely acceptable in heavy industry, modern nanotechnology-based devices cannot be produced in such a manner.

High-beam quality ($M^2 < 2$) short (sub-nanosecond) pulse lasers opened entirely new possibilities in processing due to the possibility to exploit highly nonlinear and thermal aspects of light-matter interaction [6] alongside a huge variety of already available linear process-based interaction regimes. The usage of optical nonlinearities enabled to use any wavelength for any given material, because there was no more necessity to optimize the process around the energy introduction to the process via direct absorption [7]. Therefore, simple solid-state Nd:YAG laser could be used as long as the intensity was high enough for nonlinear processes to take place. This highly supplemented popular gas lasers (CO_2 or Eximer), which, although highly advanced in the present day, still require circulating gas and special optical components to operate at industry-relevant power regimes, making them substantially more complicated than solid-state counterparts. Additionally, such processes have intensity thresholds and thus are naturally confined only to the high-intensity regions of laser irradiation, making them highly selective. Combined with pulse length and spacing (i.e. repetition rate f)-induced control of thermal effects, it allowed to achieve processing precision down to the micrometer scale with throughput suitable for industrial use.

Diode pumped solid-state femtosecond lasers are the pinnacle of short pulse generation in visible and near-infrared wavelengths [8]. Due to the ultrahigh intensities (above GW/cm^2) achievable with such radiation, nonlinear interactions are the primary channel of energy introduction to the material [6, 9]. At the same time, due to ultrafast interaction timescale, heat dissipation from the light-affected region can be made nominal, resulting in nearly material-independent ultrahigh-precision (down to the nanometer scale) processing [6, 9]. Thus, in this article, we will give an overlook on how femtosecond pulses are applied for high-precision subtractive (ablation, cutting, and etching), additive [lithography and laser-induced forward transfer (LIFT)], or hybrid subtractive-additive manufacturing. The potency of these processing techniques is demonstrated by the ever-increasing impact to the industry, shown both by the growth in femtosecond laser production and associated industrial sectors. Finally, general directions where the technology and field in general are moving will be provided.

2 Femtosecond lasers in material processing

2.1 Interaction between materials and ultrashort pulses

In a very generalized case, a material can transmit, reflect, scatter, or absorb light. In the last case, energy is introduced to the material. If energy is sufficiently high, it can induce various changes in the material. Selective exposure of the material with a sufficient amount of laser light to induce desired changes in the medium is the main premise of laser material processing.

When lasers were first introduced, the main pathway for energy introduction to the material was linear absorption. In that case, photons of energy matching or slightly exceeding bandgap energy of material E_g are used to excite material and induce melting or evaporation (Figure 1A). As photon energy E_p is dependent on emission wavelength λ as $E_p = hc/\lambda$, appropriate λ has to be used for any material. Therefore, various materials called for different lasers to be used in fabrication. For instance, CO_2 lasers were widely adopted for metal cutting [10], whereas Excimer lasers became popular in polymer processing [11]. It is important to note that the popularity of some laser systems in the industry (for instance, CO_2) was also helped by the availability of huge average power (>kW).

With the advances in laser technology, pulsed lasers operating at decreased pulse lengths became available. First, Q-switched lasers allowed to compress pulse duration to approximately nanosecond range [12]. Then, the introduction of active mediums with broadband gain

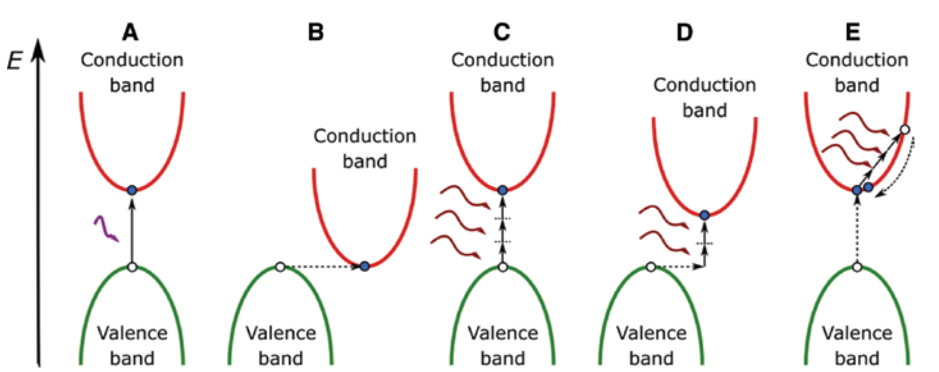

Figure 1: Simplified schematics of various excitation regimes found in laser material processing: (A) one-photon absorption, (B) tunneling ionization, (C) multiphoton excitation, (D) hybrid between multiphoton and tunneling ionization, and (E) avalanche ionization.

(from tens to hundreds of nanometers) and mode synchronization pushed the limit of pulse duration to almost one optical cycle [13]. In contrast, due to available spectral bandwidths of some more common/practical active mediums (for instance, Yb:KGW), pulse broadening during amplification and propagation through optical chain in most material processing regimes pulses of more than tens of femtoseconds are used. The main advantage of pulsed laser operation is a sharp increase in the peak power P_p, which can be calculated as

$$P_p = \frac{P}{f\tau}, \tag{1}$$

where P is the average laser power, τ is the pulse duration, and f is the laser repetition rate. Thus, P_p increases as τ becomes shorter. For instance, if a laser $P=10$ W is operating at $\tau_1=30$ ns and $f=1$ kHz, then $P_{p1}=330$ kW. However, in the case of $\tau_2=300$ fs and $f=1$ kHz, $P_{p2}=33.33$ GW (if we take the same $P=10$ W). These τ and f are common in today's commercial laser systems operating in both nanosecond and femtosecond regimes. It is obvious that decreasing τ increases P_p by the same order of magnitude. Note that here we are neglecting some more complex ultrashort pulse aspects, such as the requirements for the active medium or pulse contrasts as these are beyond the scope of this tutorial.

Such a sharp increase in P_p can be paired with focusing optics to achieve very high light intensities I in the focal point. Indeed, in the most general case, I can be calculated as power to the laser spot:

$$I = \frac{P}{\pi w_0^2}, \tag{2}$$

where w_0 is the laser spot radius. It is tied to focusing optics via numerical aperture (NA) as $w_0=0.61$ NA/λ considering Gaussian light distribution. Thus, peak I in the middle of a Gaussian laser spot can be calculated as

$$I_0 = \frac{2P}{f w_0^2 \pi\tau}, \tag{3}$$

The presented formalism is valid for perfect Gaussian beams. For real beams, M^2 parameter should be considered. Then, $w_0=M^2 0.61$ NA/λ, resulting in bigger laser spot and subsequent drop of I in the laser spot.

I is proportional to the square of electric field of the light. High I values enable nonlinear light-matter interactions. In the case of transparent medium, two distinct nonlinear light-matter interaction regimes can be deduced: multiphoton and tunneling ionization. Which regime is prevalent shows the Keldysh parameter [14]:

$$\gamma = \frac{F}{e}\sqrt{\frac{\varepsilon_0 cmnE_g}{I}}, \tag{4}$$

where F is the frequency of the light, e is the electron charge, ε_0 is the dielectric permittivity, c is the speed of light, and n is the refractive index of the material. It is considered that if $\gamma \ll 1$, the tunneling ionization is a dominant process. In that case, relatively slow oscillations of electric field of the light severely perturb the energy level system of a material for long enough for an electron to tunnel from valence band to conduction band. The higher ω results in shorter perturbations to the electron system, which minimizes the possibility for electron tunneling. Therefore, when $\gamma >> 1$, the dominant process is a multiphoton excitation. It is important to note that multiphoton ionization probability p is highly dependent on I and E_g:

$$p = \sigma_k I^k, \tag{5}$$

with k showing the number of photons, so $kE_p \geq E_g$ – a condition needed for multiphoton absorption. Also, p is diminishing as k increases, meaning that lower-order nonlinearities (for instance, two-photon absorption) has higher probability than the higher-order process. Contrary to multiphoton absorption, tunneling ionization is a lot less dependent on the E_g of the material [14, 15]. It is important to note that, for some materials and experimental conditions (for example, fused silica and 1030 nm laser radiation), $\gamma \sim 1$, which denotes that there is no dominant process, resulting in part multiphoton, part tunneling ionization.

Finally, an avalanche ionization has to be discussed as well. The electron in the condition band can interact with the electric field of light by being accelerated, resulting in increase in the kinetic energy E_k. If E_k exceeds the E_g by the time the electron reaches another atom, it can transfer its energy to another electron, thus exciting it to the conduction band [16]. This results in an ever-increasing excited electron count $n(t)$ over time t, which follows the exponential growth law:

$$n(t) = n_0 e^{\beta t}, \tag{6}$$

where n_0 is the initial electron count and β is the avalanche ionization rate. As this process happens over time, the possibility of it being noticeable when ultrashort (sub-100 fs) pulses are used is nominal. However, when pulse duration is increased to hundreds of femtoseconds, the range at which most of the modern amplified laser systems operate, it can become comparable or even exceed multiphoton ionization by the amount of excited electrons. Also, there has to be some initial electrons for this process

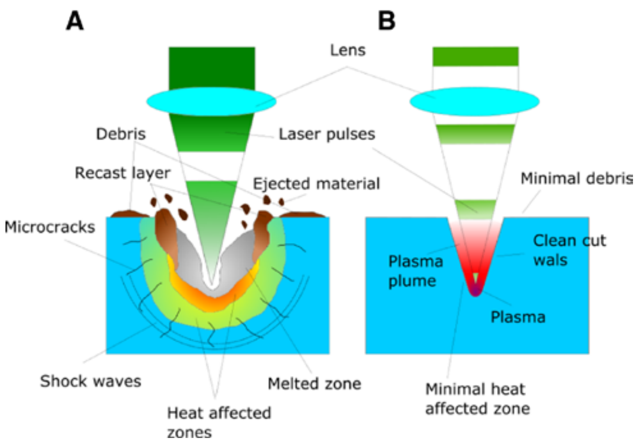

Figure 2: Schematics highlighting the differences in ablation using nanosecond (A) and femtosecond (B) pulses. Due to high light intensity in the focal point and superb control of thermal effects, substantially better-cut quality can be achieved with femtosecond pulses.

to occur. These could be either free electrons occurring due to impurities in the material or excited via other nonlinear processes [16, 17]. The efficiency of the process decreases with the shorter wavelengths (especially <1 μm) [18] and can be considered to scale linearly with *I* [18, 19].

2.2 Subtractive processing

One of the key technological operations is the cutting of a material. Throughout history, various mechanical cutting methods were developed. Up to this day, they offer a relatively simple way to produce required shapes out of the bulk material and are widely used. In contrast, they have some limitations and drawbacks. In simplified terms, to efficiently cut material of a given hardness, a harder material is needed. This is a basis of the Moth scale, showing which minerals can scratch other substances. However, any mechanical processing results in tools getting dull over time and potentially introducing their own material to the cut. Laser light, in contrast, interacts directly with the material on a quantum level and is contact-less, meaning that there is no limitations in terms of the processable material and no tool-induced contamination. For this reason, laser material processing gained huge popularity in a lot of different fields where cut quality is one of the key parameters and/or the material in question is hard to process using conventional tools.

Femtosecond pulses introduce several key differences to laser cutting process. First, as mentioned before, there is no need to directly target E_g with laser's λ if the nonlinear interaction regime is chosen for processing. This highly expands the range of materials that can be directly structured, including live tissue [20], polymers [21], metals [22], glasses [23], and crystals [24]. Furthermore, the timeframe of interaction between light and single atoms in the focal region becomes substantially shorter than heat dissipation from the affected region. Thus, heat effects can be highly localized and suppressed, leading to the so-called 'cold processing' (Figure 2), which can be used for great effect for ultraclean cutting and drilling with feature sizes down to micrometers with minimal heat-induced damage to the surrounding area [6, 9, 25] (Figure 4A). This allows femtosecond-based cutting and drilling to exceed precision of any other kind of the direct machining technique.

Cutting is an example of a very straightforward interaction between femtosecond laser and matter. However, more precise control of light parameters can yield true nanofeatures on a surface of a material with feature sizes

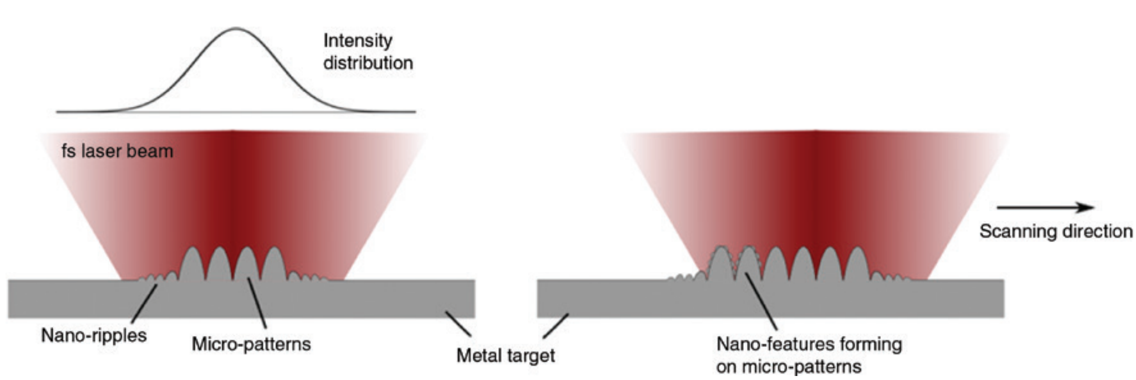

Figure 3: Formation of hierarchical surface patterns translating sample with femtosecond laser spot with Gaussian *I* distribution. The central part of the beam forms micrometer features. Subsequent exposure to the outer part of the laser spot that it is moving induces nanogratings on top of the micrometer features. If nonfemtosecond pulses were used, uncontrollable thermal effects would make the formation of hierarchical structures highly complicated.

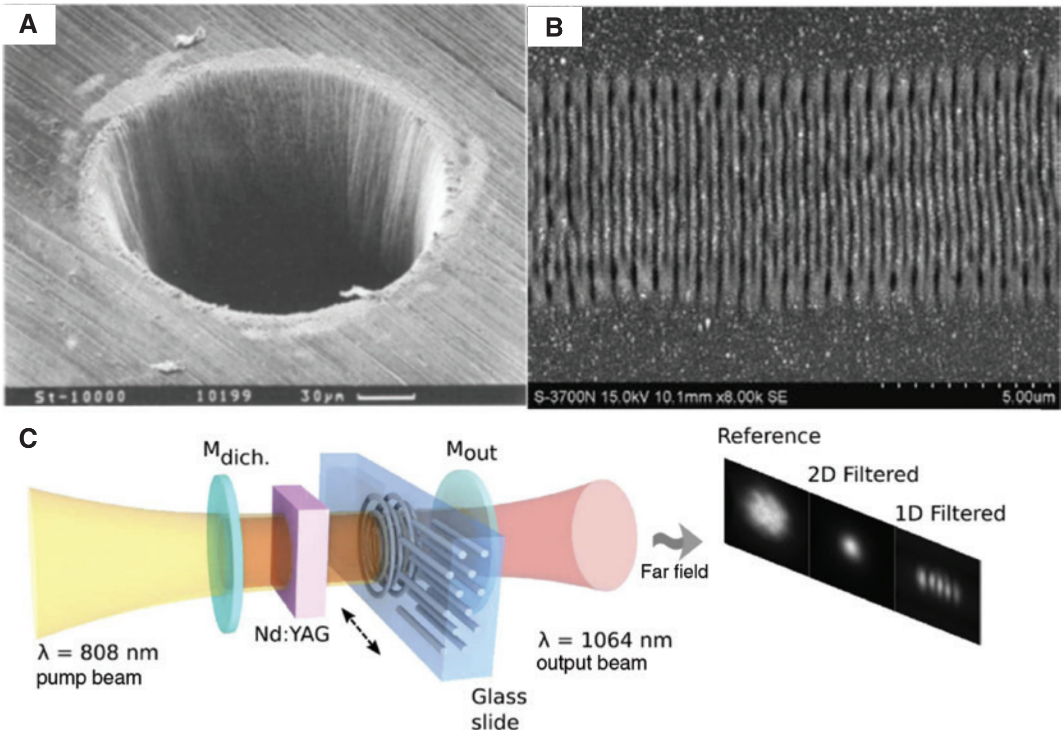

Figure 4: Examples of high-precision femtosecond processing used in different applications. (A) Example of a hole cut in 100-μm-thick steel foil with extreme precision and minimal heat affected zone achieved using Ti:sapphire laser, 200 fs pulse duration, and E_{pulse} = 120 μJ [6]. (B) Typical image of subwavelength surface patterns formed on the metal surface using femtosecond laser [26]. (C) Schematics of microchip laser enhanced by integrated spatial filtering achieved using femtosecond laser produced photonic crystal [27].

down to nanometers [28]. Although the formation of surface patterns can be induced with longer pulsed lasers as well [29], femtosecond pulses excel in this role and allow to create not only true nanopatterns but also more intricate hierarchical micro-nano textures [30]. It is the result of the relative suppression of heat effects, present with longer laser pulses, and the possibility for material to have different interactions with Gaussian laser spot as it is translated on the surface [31]. In that case, the central, high-intensity part, is responsible for the creation of microfeatures, whereas the periphery of laser spot induces nanogratings (Figure 3). There are several kinds of surface ripples, with the sizes from $\lambda/2$ and less, resulting due to various light-matter interactions at the surface [26, 32, 33] (Figure 4B). The orientation, depending on the prevailing mechanism, can be perpendicular (in most cases) to the light polarization or parallel [26, 32, 33]. The patterning of this kind exceeds chemical or coating-based methods as there is more control of the texture's shape and orientation and they can be made on virtually any material [30, 34–36]. For this reason, it is considered to be a key enabler in high volume production of functional surfaces needed for antifouling, anti-icing, and similar applications.

Finally, the internal modifications of a transparent medium via femtosecond pulses should not be forgotten (Figure 5). It is a powerful tool to produce integrated functional elements into transparent medium [27, 37] (Figure 4C). Furthermore, the resulting modification can occur in the form of volume nanogratings, which have useful functional properties for controlling the light passing through the sample [38–40]. Also, it was shown to greatly increase the rate at which modified volume is dissolved in etching solution [41] (Figure 6). Therefore, it can be used to create true embedded 3D glass and crystal structures via laser exposure and subsequent wet etching [42, 43]. Although it is applicable only for transparent mediums, it exceeds direct ablation in the flexibility of created 3D shapes. Direct material removal can be used for intricate 3D structure creation [44], but etching allows to embed channels and similar objects into glass volume [43]. Furthermore, if experiment conditions are correct, taper-less channel walls can be made with surface roughness down to submicrometers [45]. For these reasons, laser-assisted selective etching (LASE) was used with great effect in the field of microfluidics, where precision and quality enabled by LASE are very

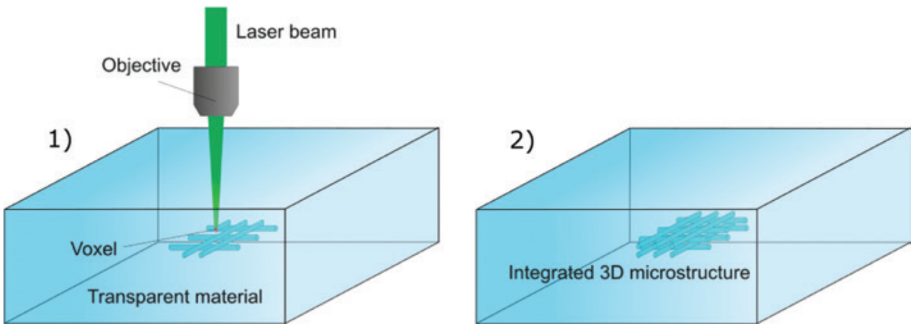

Figure 5: Principle of inscribing modified regions inside a bulk of transparent medium. (1) Laser is focused into a volume, creating local modification. Refractive index of the material can be changed and volume nanogratings or voids can be induced depending on the *I* used. (2) After laser exposure, the structure is ready to be used.

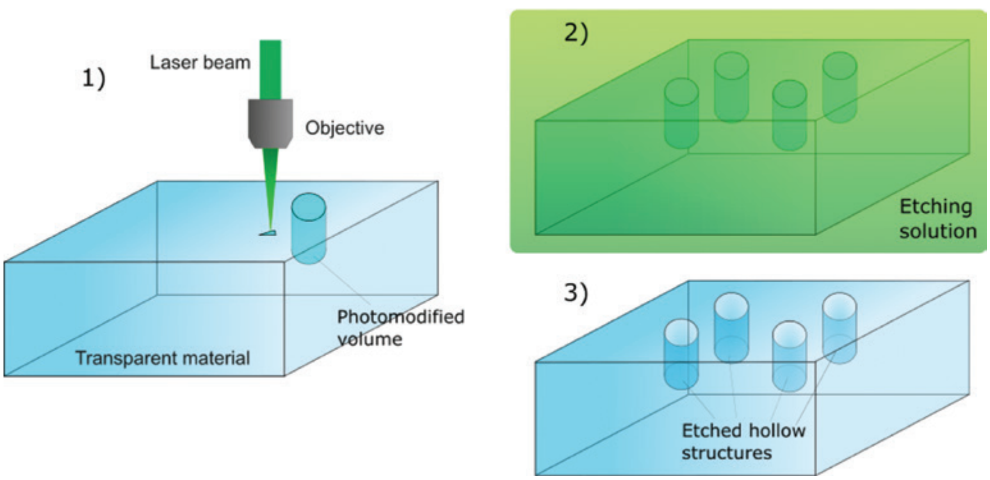

Figure 6: Steps needed for LASE: (1) material modification using femtosecond laser to create volume nanogratings that increase the etch rate of the modified regions, (2) etchant (in most cases, HF) is applied to remove exposed regions, and (3) final structure after being taken out of etchant and with femtosecond laser exposed regions removed.

attractive for the functionality of the most advanced lab-on-chip systems.

2.3 Additive structuring

Although subtractive processing is a powerful tool in manufacturing, it also has some inherent disadvantages. Every method relying on material removal generates some technological waste that has to be removed during technological process and handled afterward [46]. Also, producing true 3D shapes is a complicated endeavor even in the case of LASE. Additive manufacturing, in contrast, excels in this regard [4, 5]. With the addition of femtosecond lasers, additive manufacturing can be pushed to new capabilities in terms of flexibility and achievable feature sizes.

A way to exploit multiphoton processes taking place when ultrafast pulses are interacting with the material is 3D laser lithography (3DLL; Figure 7). In standard lithography, ultraviolet-sensitive photoresists are polymerized via one-photon absorption [47]. However, if nonlinear absorption is used, polymerization can be induced in very small volume denoted by the focal point of a high NA (>0.3) focusing objective. In most cases, two-photon absorption is employed [48, 49]; hence, it is referred as two-photon polymerization in a lot of literature (although different interaction regimes can also be used [50, 51]). This allows printing with volume pixels (voxels) with supreme selectability at subdiffraction limited resolution (normally around several hundred nanometers [52, 53]), allowing true 3D architectures [54]. As a result, 3DLL was employed for great effects in the fields (Figure 8) of micromechanics [55, 58], biomedicine [59, 60], microfluidics [61, 62], microoptics [56, 63], and photonics [57, 64] out of a wide selection of materials [65, 66] that can be additionally combined in a single sample enabling 4D

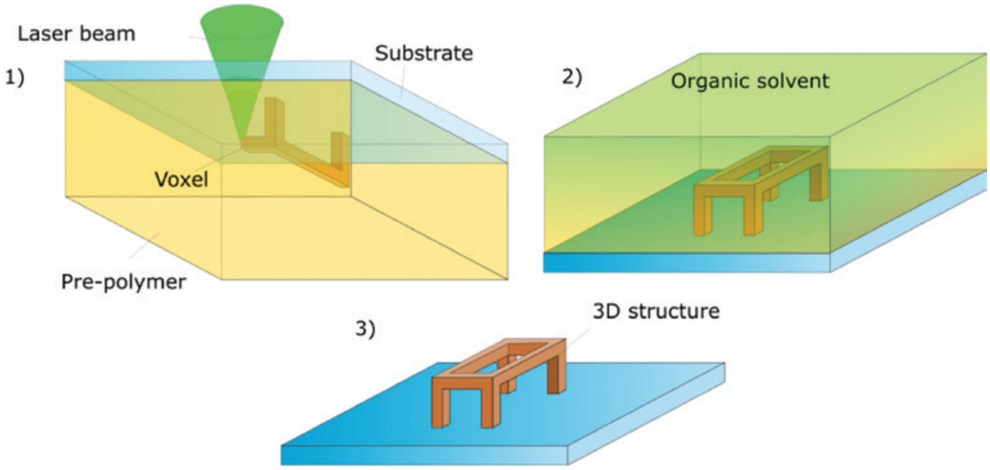

Figure 7: Schematics of multiphoton polymerization-based 3DLL: (1) writing of a structure in prepolymer, (2) development, and (3) final structure.

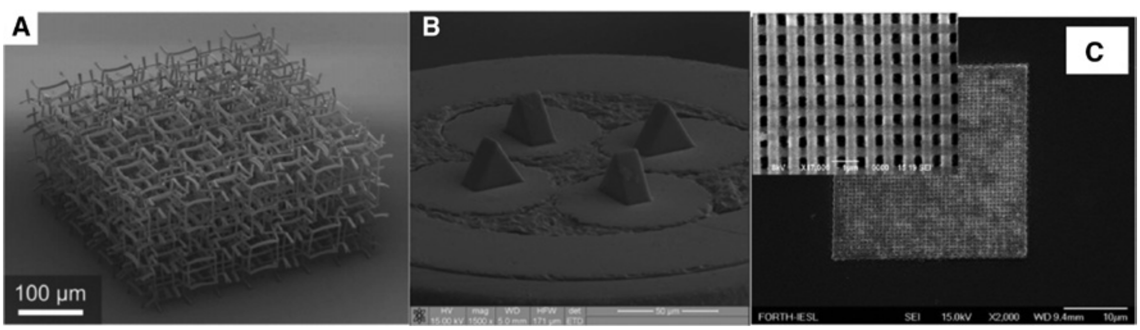

Figure 8: (A) Example of mechanical metamaterial based on complex 3D architecture and selectively varied cross-linking degree in the structure, which allows to control the thermal expansion of the whole structure [55]. (B) Microoptical elements printed on multicore fiber used for optical manipulations [56]. (C) High-resolution photonic crystal metal coated with silver for enhanced plasmonical response needed for sensing applications [57].

printing [60, 67]. If needed, the resolution can be further increased to nanometer scale with the expense of translation velocity (limited by the reaction rate of special material) by employing STED-based methods [68, 69]. Finally, objects can be made directly on special substrates [70, 71], resulting in one-step alignment-free manufacturing of functional devices.

The capabilities of 3DLL can be further expanded by the smart manipulation of materials and postprocessing. First, most of the materials available for 3DLL can be mixed with organic and inorganic additives giving desired properties to the material during or after fabrication. It can be enhancement in photosensitivity during laser exposure [17, 72], changes in refractive index [73], physical properties [74], or desired luminescent response [72, 75] of a final structure. Alternatively, structures can undergo various postprocessing steps, such as pyrolysis or etching, resulting in enhanced physical resiliency [76], higher resolution [77], or both [78] while retaining true 3D architecture. These methods help to greatly expand the capabilities of 3DLL adding to the already impressive flexibility of the technique.

One of the most exotic additive manufacturing techniques based on ultrafast light-matter interaction is LIFT [79]. The premise of this technique is transferring energy from the laser pulse to the sample, so it is physically detached from the donor sample and then lands on the receiver. If the reaction is controlled correctly, metals [80], polymers [81], and living cells [82] can be transferred. This way, single-shot multimaterial printing is also possible, meaning that functional entire devices can be produced using LIFT [83]. Resolution can be tuned in a relatively wide range from targeted nanoparticle fabrication [84] to the creation of parts tens of micrometers in overall size [85]. Overall, although it is a highly promising technique, it still requires a lot of tuning and improvements before it becomes a widespread solution.

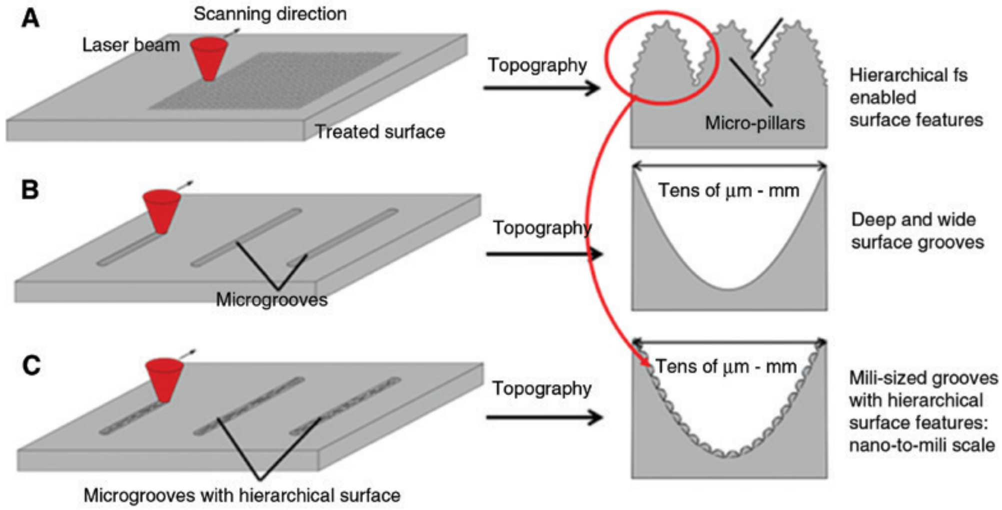

Figure 9: Femtosecond lasers allow to produce surface patterns at both hierarchical nanolevels (A) and microlevels (B); however, if correct exposure parameters are used, modifications on both scales can be achieved (C).

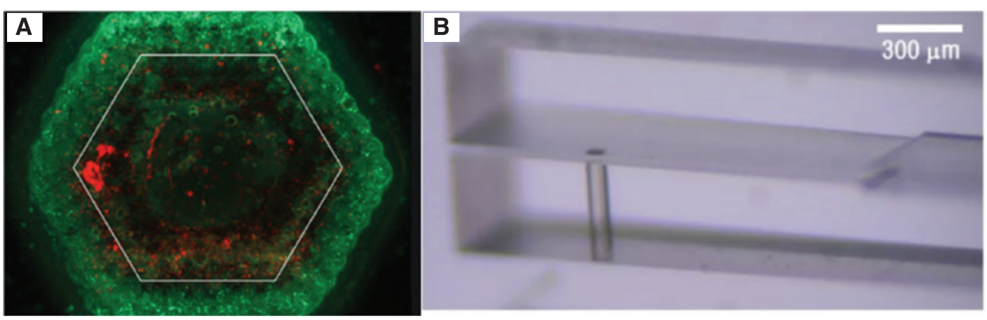

Figure 10: (A) Example showing a 3DLL-made hexagonal scaffold seeded with various cells using LIFT [89]. (B) A chemically inert glass cantilever produced using LASE with integrated polymeric rod. The rod can swell or shrink due to immersion into different organic solvents, making the cantilever move, thus resulting in a passive medium-sensitive sensor/actuator [90].

2.4 Hybrid manufacturing

In most cases, it is considered that a specific tool should be used for a task it is best suited for. However, femtosecond laser is a unique tool in a sense that many different highly tunable and adaptable processing regimes can be achieved with it. Therefore, it is more than normal that ultrafast laser-based manufacturing techniques are paired with other fabrication methods or between each other. Such pairing is called hybrid manufacturing. Currently, it is gaining more and more popularity in the field of femtosecond laser-based processing. For instance, 3DLL has an inherent throughput limitation as it is a point-by-point exposure-based direct laser writing (DLW) technique. Thus, pairing it with other additive manufacturing techniques that have worse resolution but higher structuring rate is an interesting prospect [86]. Alternatively, 3DLL can be used to produce ultrahigh-precision masters for replication technologies [87], including even some true 3D architectures [88]. Additionally, 3DLL can be paired with LIFT [89], as 3DLL can rapidly print scaffolds out of the required material needed for cell growth and LIFT can selectively seed it with live cells (Figure 10A). Similarly, subtractive processing can be used to first induce relatively big (approximately tens of micrometers) grooves on the surface of the material and then, after parameters are changed, induce surface nanogratings (Figure 9). Different pulse lengths can be combined for enhanced result [91]. Overall, the idea is that different manufacturing techniques and regimes can be used in tandem to achieve the best possible result.

One of the key areas where hybrid manufacturing was exploited for great effect is microfluidics. 3DLL was used to integrate various functional structures into glass channels that were manufactured using femtosecond laser [61, 62, 90] (Figure 10B). In the latter case, wide tunability of modern amplified laser sources is exploited. This opens an opportunity to replace most single purpose with hybrid femtosecond laser-based processing workstations. Although it might require quite a big initial investment, saved floor footprint and simplified logistics should have a highly positive long-term impact if such transition is done.

3 Industrial appeal

If technology becomes mature enough and can solve otherwise inaccessible challenges, it eventually starts to generate interest from the industry. Then, the field can develop at accelerated rate using business provided resources and solve real-life application dictated challenges. Ultrafast laser material processing is no exception. The advances in the science field of ultrafast material processing gathered quite a substantial attention from the industry. As a result, the femtosecond laser industry is booming with substantial yearly growth motivated by both the necessity to use these light sources for scientific purposes and the growing implementation in industrial facilities. For this reason, industrial-grade femtosecond laser systems are expanding in several key areas. Increasing maximal P while maintaining femtosecond pulse duration and good beam quality is regarded as a way to highly increase processing throughput via possibility to use large laser spot or beam splitting. Flexibility in tuning pulse parameters while maintaining relatively high P is another area where a lot of improvement is expected. This is needed for the propagation of hybrid manufacturing. Overall, it is expected that in time solid-state ultrafast lasers will, to most part, replace gas-based lasers.

Although laser is a key enabler in processing, associated optical chain and overall processing setup is needed to achieve the final result. Some users of femtosecond lasers prefer to buy a laser and create the workstation themselves. However, that requires understanding of laser physics and engineering. For some institutions and industrial facilities, a lot simpler solution is to just buy a finished and ready-to-use machine. For this reason, an entire segment of the industry is dedicated in commercializing femtosecond-based material processing. The differentiation here lies in that some companies prefer selling systems, some prefer services (i.e. research and development), and some specialize in both. Technologies employed can be subtractive, additive, or hybrid. Overall, this field is relatively new and constantly expanding due to the convenience of taking a finished workstation and using it as soon as possible.

4 Future of the technology

Current femtosecond laser sources are extremely advanced and developing in many different directions. Here, we mention only the most prominent trends that are relevant in the light of this tutorial. Both stand-alone oscillators and amplified systems are capable to cover a huge range of tunable parameters including τ, f, P, and λ. Further developments will be associated with the better understanding and exploitation of existing laser mediums (for instance, Er [92] and Yb [93] doped mediums) as well as the adoption of some new materials [94]. The combination of diode laser pumped solid-state lasers and fiber-based systems will allow to further push the flexibility and output parameters. Overall, the advances will be tightly tied to the necessities dictated by the science and industry alike.

Further enhancement of the throughput and quality is also highly desirable. Most of the discussed techniques are point-by-point DLW, making them inherently slow. Additionally, if volume structure is formed (for instance, LASE and 3DLL cases), it increases the time needed for fabrication by the order of 3, making volume fabrication slow. To remedy this, several solutions were proposed. Fast translation velocities (cm/s and more) can be achieved with modern positioning systems relying on linear stages [95], galvo-scanners [96], or the synchronization of both [97]. The latter solution is very attractive, as it allows to preserve unlimited working volume (needed for stitch-free printing) and nanoprecision while maintaining high translation velocities. Throughput can be further increased using multiple beams at once, which can be done using passive elements [98] or spatial light modulators (SLM) [99]. In addition, SLMs can also be used to create intricate laser beams [85] or correct deficiencies in focusing occurring due to specific processing regimes or materials [100]. Overall, although femtosecond is a well-established tool in material processing, the technology itself can be greatly improved for even more spectacular results.

5 Conclusions and outlook

The challenges posed by the modern engineering will only grow in time. It is extremely hard to predict what exact challenges will come in 5 or 10 years' time. Current trends suggest that functional devices will become more and more downsized and integrated. The widespread usage of femtosecond pulses promises to be perfect candidate to tackle these challenges with capability to produce highly intricate structures from nanometer to centimeter range out of basically any material. For this reason, it can be expected that transition from lab-to-fab will be constantly accelerating, with femtosecond lasers becoming a day-to-day tool in both scientific laboratories and industrial facilities.

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