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Introduction

Hiroaki Misawa and Saulius Juodkazis

Three-dimensional (3D) laser micro-fabrication has become a fast growing field of science and technology. The very first investigations of the laser modifications and structuring of materials immediately followed the invention of the laser in 1960. Starting from the observed photomodifications of laser rod materials and ripple formation on the irradiated surfaces as unwanted consequences of a high laser fluence, the potential of material structuring was tapped. The possibility arose of having a highly directional light beam, easily focused into close to diffraction-limited spot size, and with the arrival of pulsed lasers with progressively shorter pulse durations, the field of laser material processing emerged. Understanding the physical and chemical mechanisms of light–matter interactions and ablation (from *lat. ablation,* removal) at high irradiance began the ever widening number of scientific and industrial applications.

The arrival of ultrashort (subpicosecond) lasers had expanded the field of material processing into the real 3D realm. Even though ablation can be used to fabricate 3D microstructures the real 3D structuring of materials (from the inside) requires highly nonlinear light–matter interaction in terms of light intensity for which the ultrashort pulses are indispensable. The focused ultrashort pulses inside solid-state materials introduces a novel, not fully exploited, tool for nano-micro-structuring. The irradiance at the focus can reach ~ 100 $\mathrm{TW\,cm^{-2}}$ (1 TW = 10^{12} W) at which any material, including dielectrics, is ionized within several optical cycles, i.e., optically-induced dielectric breakdown ensues. It is noteworthy, that such irradiance is reached using low pulse energies < 0.5 μJ at typical pulse durations < 200 fs (1 fs = 10^{-15} s). Combining this with an inherently micro-technological approach, it makes this high-irradiance technology attractive in terms of its “green”, environmentally friendly aspect due to high precision and effectiveness. In theory, the inherently 3D structuring avoids a lengthy and wasteful multi-step approach based on lithography with subsequent solid-state materials growth and processing. A continuing trend of reduction of the “photon cost” of femtosecond lasers and an increase of the average pulse power at higher repetition rates places the 3D laser micro(nano)technology firmly on the list of future movers. We believe that 3D laser micro-fabrication will implement the visionary top-down

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approach of nano-technology and will show solutions for merger with the bottom-up self-assembly route currently advancing fast in its own right.

In this book, we have made a first attempt to review the state-of-the-art of the interdisciplinary field of 3D laser microfabrication for material micro-nano-structuring. The distinction of this field in terms of physical mechanisms is a 3D enclosure of the processed microvolume inside the material. In the case of dielectric breakdown by ultrashort pulses, the matter can be transferred from a solid to liquid, gaseous, and a multiply-ionized plasma state, which still possesses the solid state density. This creates unique conditions as long as the surrounding medium can hold the high temperature and high pressure microvolume of ionized material, without crack formation. Obviously, this is most feasible when the ionized volume is minute (of sub-micrometer cross-section). The chemical modifications are also radically different for in-bulk laser processing, indeed, the compositional stoichiometry of the focal volume is conserved over the radical phase changes which the matter endures at the focus. When the pressure of the ionized material at the focus becomes higher than the "cold" pressure, the Young modulus, the shock and rarefaction waves emerge. The shock-modified compressed region has unique altered physical and chemical properties and can be confined within sub-micrometer cross-sections. Material can be also chemically and structurally altered by properly chosen exposure (not necessarily by fs-pulses) and post-exposure treatment for designed properties and funcionality, e.g., 3D structuring of ceramic glasses.

Research in the 3D laser microfabrication field is prompted by an increasing number of prospective applications; however, it is usually approached as an engineering "optimization problem". The required processing conditions can be more easily found by a fast trial-and-error method using powerful computers, experiment automation tools, and software based on intelligent self-learning algorithms. Hence, understanding the underlying physical principles and review of the results achieved could help further progress in this field. This is a shared view of the group of authors who teamed up for this project. The scope of this book ranges from the principles of 3D laser fabrication to its application. Direct 3D laser writing is the main topic of the book. The mechanisms of light–matter interaction are discussed, applications are reviewed, and future prospects are outlined.

The idea of this project stemmed from the importance of nonlinear light–matter interaction; thus, first of all, the intensity (irradiance) should be known and controlled. We address the issues of light delivery to the photo-modification site, describe the mechanism of light–matter interaction, and show the versatility of the phenomena together with the broad field of application. The correct estimate of the pulse energy, duration, and the focal volume are crucial, which in the case of ultrashort pulses, is not trivial. The book starts with the theoretical Chapter 2 (E. E. Gamaly et al.) on the light–matter interaction at high irradiance inside the bulk of the dielectric. It is based on multi-photon and avalanche ionization theories developed more than 50 years ago. However, their predictions are now applied to 3D laser fabrication. Chapter 3 (M. Gu and G. Zhou) addresses light-focusing issues relevant to energy delivery and spatial distribution. Chapters 4 and 5 (X. Gu et al. and J. Buck and R. Trebino) describe the basic principles of pulse duration measurements and nonlinear optics, respectively. Chapter 6 (E. Gaižauskas) discusses a mechanism of filament formation in dielectric media. Chapter 7 (R. Haglund) surveys photo-physical and photochemical aspects of light-meter interactions. Micro- and nano-in-bulk structuring of glass is described in Chapter 8 (P. Kazansky). X-ray generation by ultrashort pulses and their potential for time-resolved structural characterization is discussed in Chapter 9 (K. Hatanaka and H. Fukumura). The applications of 3D laser microfabrication are further explored in Chapters 10–12. Fabrication of photonic crystals and their templates are described in Chapter 10 (S. Juodkazis et al.). Flexibility and versatility of 3D micro-structuring of glass ceramic is highlighted in Chapter 11 (F. Livingston and H. Helvajian). Setups, fabrication principles and different examples of 3D micro-structuring are described in Chapter 12 (A. Ostendorf et al.) by one of the leading group in the field from Hannover Laser Zentrum. All chapters are self-inclusive and can be read in any order.

Since the field of 3D laser microfabrication is growing so quickly, we tried to focus on the topics which are more general and have high potential for future advance; at the same time striking a balance between the theory and applications. Unfortunately, there was no possibility of highlighting many other very important developments, namely, non-thermal melting, imaging of photoinduced movement of atoms by ultrafast X-ray pulses, Monte-Carlo simulations of atomic movement at high excitation, laser intracell and DNA surgery, or waveguide recording.

Seminal contributions have been cited throughout the book. However, some references just show a relevant example rather than stress the first demonstration or priority (this purpose is better served in the original papers). There are a number of excellent books on the related subjects of ablation [1], laser processing of materials [2], laser damage [3], and on the basics of light–matter interactions [4, 5] which covers closely related topics. Here, however, we would like to stress that 3D laser processing stands out, with its own unique physical and chemical mechanisms of photo-structuring and an obviously increasing field of application.

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H. Misawa
S. Juodkazis Sapporo, December 1, 2005

References

1 J.C. Miller ed., “Laser Ablation”, Springer, Berlin, 1994.

2 S. M. Metev and V. P. Veiko, eds., “Laser-Assisted Microtechnology”, Springer, Berlin, 1994.

3 R. M. Wood, “Laser Damage in Optical Materials”, Adam Hilger, Bristol, 1986.

4 D. Bäuerle, “Laser processing and Chemistry”, Springer, Berlin, edition. 3rd, 2000.

5 Ya. B. Zel’dovich and Yu. P. Raizer, “Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena”, eds. W. D. Hayes and R. F. Probstein, Dover, Mineola, New York, 2002.