Three-dimensional laser nano-/micro-fabrication by femtosecond pulses

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Abstract Three-dimensional laser micro-structuring of resists, polymers, glasses, and crystals is demonstrated by the direct laser writing and holographic recording using femtosecond laser pulses. Possible applications of laser structured materials in photonics and micro-fluidics are discussed.

1. Introduction
Three-dimensional (3D) structuring of glasses, ceramics, crystals, and polymers by tightly focused femtosecond laser pulses is a promising technique for microfluidic, micro-optical and micro-mechanical applications. Tightly focused laser pulses can reach dielectric breakdown intensity (irradiance) without self-focusing when sub-1 ps pulses are used inside dielectric. Hence, a photo-structuring by 3D tightly focused laser pulses realizes the direct laser writing approach in a well controlled manner. The holographic recording is another versatile laser microfabrication approach where short sub-1 ps pulses can deliver 3D structuring over comparably large areas of sub-millimeter cross sections. Here, we outline the physical principles underlying the 3D laser microstructuring techniques: holographic and direct laser writing. We describe application of these techniques for the fabrication of 3D photonic crystals, and demonstrate some of the results achieved in this field.

2. Direct laser writing inside dielectrics
By using objective lens of a high numerical aperture NA > 1 the focal spot size and, consequently, the photomodified region can be contained within a volume of sub-micrometer cross-sections. The photomodifications can range from induced defects, color centers, polymerized voxels, and ultimately voids depending on material, focusing, and pulse energy. The mechanism of void formation [1] can be explained by nonlinear absorption and avalanche multiplication of electrons which effectively lead to ionization of the focal volume. The absorption in the plasma at focus is localized within a skin depth of tens-of-nanometers. This defines an ultimate localization of the energy delivery by a laser pulse. The temperature and pressure buildup can be large enough to generate shock wave (strong micro-explosion). For example, a 100 nJ laser pulse can form a void under tight focusing conditions even in sapphire (Young modulus of 400 GPa). This opens new material processing routes for inert dielectrics [2,3]. Altered chemical properties of shock-affected regions inside silica glass and sapphire were
revealed by wet etching of “shocked” regions in aqueous solution of hydrofluoric acid. The maximum wet etching selectivity defined as a ratio of the etched-out length to the width of channel in silica glass, quartz, and sapphire were approximately 100, 500, and > 1000, respectively. Such 3D patterns can be used for microfluidic and sensor applications.

The 3D direct laser writing was used for micro-structuring of SU-8 resist. 3D photonic crystal templates with a stopband at a shorter than 1 micrometer wavelength have been achieved.

3. Holographic recording

One of the approaches discussed here is simultaneous recording of microstructures by interference of multiple femtosecond pulses. This technique is based on the same principles as holography and allows fabrication of periodic dielectric structures by recording 3D periodic laser beam interference patterns. Complexity and spatial symmetry of these patterns depend on the number of beams involved and their parameters (incidence angle, amplitude, and phase). Advanced control of the patterns allows to obtain body-centered cubic or tetragonal (bcc|bct) lattices will be described by means of theoretical calculations. Experimentally, the structures were recorded by interference in photoresist SU8. The multiple laser pulses having zero mutual temporal delay were obtained from a single laser beam simply and efficiently by a diffractive beam-splitter. Transmission and reflection spectra of the recorded structures showed close correspondence with the results of numerical simulation. A 5-beam hologram recorded in SU-8 without phase control (the resulting structure was body-centered tetragonal) and with the phase control, which was made in such a way that the resulting pattern was a log-pile structure. The control of the pattern was obtained by directing 5 beams onto a CCD camera without focusing and allowed to monitor and tune phases of the interfering beams before the actual sample exposure.

It is possible to record chiral patterns in resist by interfering circularly and linearly polarized beams. One practical pattern showing optical diode functionality can be made by interference of the central circularly polarized beam with six-side linearly polarized beams [4].

4. References


