**Hybrid Femtosecond Laser 3D Processing for Fabrication of Functional Micro/Nano-Devices**

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The extremely high peak intensity associated with ultrashort pulse width of femtosecond (fs) laser allows us to induce nonlinear multiphoton absorption with materials that are transparent to the laser wavelength. More importantly, focusing the fs laser beam inside the transparent materials confines the nonlinear interaction only within the focal volume, enabling three-dimensional (3D) micro- and nanofabrication. This 3D capability offers three different schemes, which involve undeformative, subtractive, and additive processing. The undeformative processing preforms internal refractive index modification to construct 3D optical microcomponents including optical waveguides inside transparent materials. Subtractive processing can realize the direct fabrication of 3D microfluidics, micromechanics, and photonic microcomponents in glass. Additive processing represented by two-photon polymerization (TPP) enables the fabrication of 3D polymer micro- and nanostructures for photonic and microfluidic components. Furthermore hybrid approach of different schemes can create much more complex 3D structures and thereby promises to enhance functionality of micro- and nano-devices.

 For example, a successive procedure of subtractive 3D glass micromachining and the undeformative optical waveguide writing realizes optofluidics for detection, manipulation, and sorting of bio samples [1]. Meanwhile, combination of subtractive 3D glass micromachining and additive TPP is not only an instrument that can tailor 3D structures but also a tool to fabricate biomimetic in vivo environment inside glass microfluidic chips [2]. Specifically, the subtractive 3D glass micromachining can flexibly fabricate 3D microfluidic structures embedded in glass microchips without a complicated procedure of stacking and bonding of glass substrates. Successive TPP can then integrate complex shapes of polymer structures with a sub-micrometer feature size due to its high fabrication resolution to create biomimetic structures inside the glass microfluidics. Thus, such advanced biochips can be utilized to study the mechanism of cancer cell invasion and metastasis [3]. Furthermore, the subtractive 3D glass micromachining followed by femtosecond laser direct write ablation and successive electroless metal platig enables selective metalization of 3D glass microfluidic chips for electrical motion control of livng cells in 3D [4]. This selective mtallization technique is also applied to fabricate 3D microfludic surface-enhanced Raman spectroscopy (SERS) sensers with an extremely high enhancement factor by formation of pereodic nanodot structures on the plated metal thin fills [5].

 This talk presents our recent achievements on fabrication of functional 3D micro- and nano-devices including microfluidics, optofluidics, and microsensors based on hybrid approaches of femtosecond laser 3D processing.

**References**

[1] K. Sugioka, Y. Hanada, and K. Midorikawa, “Three-dimensional femtosecond laser micromachining of photosensitive glass for biomicrochips", Laser Photon. Rev. **3**, 386-400 (2010).

[2] D. Wu, J. Xu, L. Niu, S. Wu, K. Midorikawa, and K. Sugioka, “In-channel integration of designable microoptical devices using flat scaffold-supported femtosecond-laser microfabrication for coupling-free optofluidic cell counting”, Light Sci. Appl. **4**, e228 (2015).

[3] F. Sima, H. Kawano, A. Miyawaki, L. Kelemen, P. Ormos, D. Wu, J. Xu, K. Midorikawa, and K. Sugioka, “3D biomimetic chips for cancer cell migration in nanometer-sized spaces using “ship-in-a-bottle” femtosecond laser processing”, ACS Appl. Bio Mater. **1**, 1667-1676 (2018).

[4] J. Xu, H. Kawano, W. Liu, Y. Hanada, P. Lu, A. Miyawaki, K. Midorikawa, and K. Sugioka, “Controllable alignment of elongated microorganisms in a 3D microspace using electrofluidic devices manufactured by hybrid femtosecond laser microfabrication”, Microsystems Nanoengin. **3,** 16078 (2017).

[5] S. Bai, D. Serien, A. Hu, and K. Sugioka, “3D microfluidic SERS chips fabricated by all-femtosecond-laser-processing for real-time sensing of toxic substances”, Adv. Func. Mater. 28, 1706262 (2018).

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