Spatial Light Modulator Speeds Femtosecond Laser Processing

Femtosecond laser material processing offers several advantages, including high spatial resolution and reduced thermal destruction. The high spatial resolution occurs because laser pulses can be focused tightly in a transparent material, at which point multiphoton absorption, optical field ionization, and a corresponding Coulomb explosion can occur in a submicrometer-sized location. This enables microfabrication in transparent materials. A drawback exists, however, in that such fabrication requires a very large number of processing points. This means laser processing throughput must be radically improved.

Yoshio Hayasaki and a research team at the University of Tokushima (Tokushima, Japan) set out to create a holographic femtosecond laser processing system capable of parallel, arbitrary, and variable patterning. They accomplished this using a spatial light modulator displaying a hologram in the femtosecond laser processing system—namely, an amplified femtosecond laser system and a liquid-crystal spatial light modulator (LCSLM).

In the system, the femtosecond laser pulse is diffracted at the LCSLM to form the desired processing pattern at the Fourier plane of a primary lens. A secondary lens then reduces the processing pattern, and a tertiary lens—a 40X microscope objective lens with a numerical aperture of 0.5—applies the pattern to a sample. The LCSLM consists of a parallel-aligned nematic liquid-crystal spatial light modulator coupled with a liquid-crystal display and a 680-nm laser diode. The system can display computer-generated holograms (CGHs) in real time.

“We fed the computer-generated hologram to the LCSLM from a personal computer after we had calculated it with an iterative Fourier transform algorithm,” Hayasaki says. “To get uniform peaks in the target pattern, we evaluated the CGH produced in each iteration with an error equation that said E = 1 – \( I_{\text{min}} / I_{\text{max}} \), where \( I_{\text{max}} \) and \( I_{\text{min}} \) are the maximum and the minimum intensities at the peaks we wanted. That way, we could select the CGH with the least error to do the laser processing.”

The team’s computer could calculate 50 iterations of 512 \( \times \) 512-pixel CGHs in just 27 seconds. Nevertheless, the CGHs had to be calculated in advance and stored for use when making multiple microfabrications at high speeds.

“We set up a sample that consisted of an ordinary glass microscope cover slip on a glass slide,” Hayasaki says, “and we gave it a good ultrasonic cleaning in ethanol and water. We observed the processed area with an optical microscope, and measured the nanometer-scale structure of the processed area with an atomic force microscope [AFM].”

Hayasaki’s initial experiment was composed of parallel femtosecond laser processing in which a nine-beam target pattern was used to calculate the CGH, which was reconstructed optically at the Fourier plane P. The total irradiation energy at P was 7.91 µJ, and the total diffraction efficiency of the nine beams was 86.2%. The AFM image showed a line of circular pits with a minimum diameter of 1.29 µm, a maximum of 1.40 µm, and a deviation of up to 7.7%, while the deviation from peak intensity came to 42%.

Hayasaki’s team also demonstrated an experimental variable parallel femtosecond laser processing technique using a combination of holographic and scanning techniques. Each character in the image “TOKUSHIMA UNIVERSITY” was fabricated with a single pulse, and the repetition rate of the femtosecond laser pulses was 2 Hz, Hayasaki says. “We changed the holograms at the same time we moved the stage, which went at a constant speed of 52 µm per second from right to left. We calculated 19 holograms in advance and set the irradiation energy on the plane P at 143.2 µJ. Therefore, we have proved the capability of our system to arbitrarily process at a 2-Hz repetition rate.”

Kazuyoshi Itoh of the Graduate School of Engineering at Osaka University (Osaka, Japan) says, “Hayasaki and his team opened a new field of lightwave control in femtosecond processing. The advantage of this method may be possible simultaneous correction of wavefront aberrations along with parallel writing.” —Charles Whipple