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Pico versus femto in micromachining

Guerman Pasmanik

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THE DEVELOPMENT OF LASERS PRODUCING PICOSECOND PULSES IS EASIER THAN THAT FOR FEMTOSECOND LASERS.

Development of high-repetition-rate femtosecond lasers is being stimulated by a large number of applications in material processing, mainly in micromachining. From a physics point of view this processing can be defined as material ablation in a thin surface layer affected by laser pulses, without significant heat exchange with surrounding material. Usually in metals, laser pulses are absorbed by electrons. In a few picoseconds these electrons transfer their energy to the lattice. In non-metals, for example semiconductors and dielectrics, photo- and avalanche ionizations are responsible for initial absorption of laser pulses, and with further processing similar to the scenario that takes place in metals.

In the case of ultraviolet (UV) irradiation, material ablation with its subsequent conversion into plasma can occur at temperatures below the usual vaporization level. Apparently, rapid plasma creation and ablation in a thin layer without affecting adjacent layers is possible when heat does not dissipate from the absorption zone. This occurs if the laser pulsewidth is shorter than the heat diffusion time, which is determined mainly by the depth of heated area.

The diffusion time for heated areas in metals is ~1ps due to the shallow skin layer depth (around 100 Å). For semiconductors and transparent dielectrics the depth of the absorption zone is considerably greater and can vary during the ionization process. This depth usually exceeds 1000 Å. Adding an ionizing irradiation (for example UV) triggers the creation of free electrons, which absorb pulses in a thinner layer. This reduces the depth of the absorption zone while simultaneously decreasing the minimum pulse energy required for ablation (compared with the energy of plain IR pulses). Typical heat diffusion times for the heated area in semiconductors and dielectrics are greater than those in metals and could be in the range of tens or even hundreds of picoseconds. From this point of view processing of glass and other transparent dielectrics does not necessarily require the use of expensive femtosecond lasers but could be achieved with longer laser pulses, although these pulses should be shorter than 50-100 ps.

Direct comparison of CCD camera images of holes ablated in fused silica as a function of pulse energy for two different pulse durations (140 fs and 5 ps) demonstrated that, despite the difference in ablation threshold, the quality of the produced holes did not vary significantly.

In dielectrics ablation in the field of picosecond pulses at a near-IR range depends on the number of pulses focused into a single spot. An increase in the number of pulses up to 10-20 shots decreases the threshold ablation energy from 5-10 J/cm^2 to the values typical for femtosecond pulses (about 1-3 J/cm^2).[2] However an excessive increase in the number of picosecond pulses affecting the surface degrades the material processing quality. The optimum number of pulses required to most effectively mark or cut transparent dielectrics, with a preset speed of movement of the sample, depends on material and the laser's wavelength and pulse duration.

Picosecond pulses providing the non-thermal mechanisms of ablating also can be used for resecting tissue. One of the most attractive laser neurosurgery applications is removal of brain tissue. Authors3 specified a pulse duration of less than 50 ps, a pulse energy of 2.5 mJ, a repetition rate of up to 4 kHz, and M2 of less than 3 as laser parameters fit for a neurosurgical system.

Picosecond lasers

The development of lasers producing picosecond pulses is easier than that for femtosecond lasers. There are several types of high-repetition-rate diode-pumped picosecond lasers available. The first are passively modulated modelocked lasers (mainly Nd:YAG or Nd:YVO4) producing pulses with durations of few picoseconds and energy up to hundreds of nanoJoules.4 When the beam from these lasers is focused into micrometer-sized spots it is enough to efficiently process material, forming pixels or voxels for 2D or 3D structures used for optical storage.5 A second type are microchip Nd:YAG lasers with a passive Cr4+ YAG Q-switched saturable absorber, which emits pulses with tens of microJoules with durations of a few hundreds picoseconds.6 The output of these microchip lasers has cut clean 5µm-wide lines in the metallization on semiconductor wafers and drilled holes through substrates.6 This IR output can be easily converted into the second and even third harmonics, but obtaining fourth and fifth harmonics with reasonable efficiency is more difficult.

Finally, all the solid-state diode-pumped lasers with Raman pulse compression produce output with pulse durations of tens of picoseconds and pulse energy around 1 mJ.7 These lasers are employed for glass marking (see Figure 1).

Conversion of IR pulses into the UV range provides numerous advantages8 that become prominent with picosecond pulses. First, the conversion efficiency from IR into UV range is more easily achieved for powerful picosecond pulses than for nanosecond pulses. Second, picosecond UV pulses allow reduced heat-related damages, such as charring around holes in plastics. They also increase material removal rate (volume extracted per 1µJ of incident pulse energy), which improves the quality of marking.

This makes UV picosecond diode-pumped Raman lasers with repetition rates around 5-10 kHz and short wavelengths (up to 200 nm) promising for processing transparent diel-ectrics. Currently developing techniques of simultaneous surface illumination by UV, visible and IR pulses based on these lasers also looks quite attractive.

Quality control

Fine-tuning or processing of transparent dielectrics requires a specific quality control method to examine the marks made by the laser beam on the surface of the sample. This quality control can be conducted using a simple device where a singlemode beam of a probe laser is focused in a 4-5 µm spot on the surface of the sample. The sample is moved so the laser's beam scans along the direction perpendicular to the marks on the surface. A typical dependence of intensity of the probe beam passing through the glass sample is presented in Figure 2. Beam intensity between the lines differs from that for the beam passing outside of the lines, and this difference (IA / IB ratio) reflects the quality of marking. A similar dependence at 355 nm demonstrates greater depth of lines with lower laser pulse energies.

Guerman Pasmanik is president of Passat Ltd., Toronto, Ontario, Canada. He can be reached by e-mail at guerman@passatltd.com or (T) 416/661-9633.

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