Processing of transparent materials with ultra short pulse lasers

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Abstract

Laser processing of transparent materials using ultrashort pulse lasers is widely used not only in scientific laboratories, but also on the mass production lines. Depending on the specific application, the fundamental IR (e.g. 1030 nm) or its harmonics (green, UV) may be selected for optimum processing. A laser allowing flexible adaption of its pulse parameters like energy, repetition rate and pulse duration can be of decisive advantage. We present the results of application of Pharos laser for dicing, cutting, nanostructuring of different transparent materials, where pulse energies of few hundreds of microjoules are required. To showcase the unprecedented flexibility and stability of the laser, we also demonstrate the results of transparent material modification with submicrometer resolution for creation of sophisticated 3D structures, such as transmission diffraction gratings, radial polarization converters, etc.

Keywords: femtosecond laser; laser material processing; radial polarization converter

1. Pharos Laser for material processing

Processing of transparent materials with lasers has become a fast growing field of research and technology and has been adapted by the industry as a standard. The growing interest in femtosecond laser material processing is related to its unique capabilities: inducing highly nonlinear processes, altering properties of materials without excessive production of heat, inducing extremely high pressures, and modifying almost any transparent medium with sub-micron resolution.

Pharos laser with its unique parameters is a primary choice for transparent material processing. Use of solid state laser diodes for pumping of Yb-doped medium ensures extremely stable output (Fig. 1), significantly reduces maintenance costs and provides long laser lifetime. Tunable parameters include: pulse duration (190 fs – 10 ps), repetition rate (1 kHz to 1 MHz), pulse energy (up to 1.5 mJ) and average power (up to 15 W). Most of Pharos output parameters can be easily set via control pad or a PC.

Pharos laser can be equipped with optional wavelength converters providing high power harmonics radiation at 515 nm, 343 nm and 257 nm wavelengths. Harmonic generators are designed to be used in industrial applications where single output wavelength is desired. Modules are mounted directly on the output of the laser and wavelength selection is integrated into the control system.
2. Use of femtosecond laser pulses for radial/azimuth polarization converter manufacturing

Tight focusing of a femtosecond laser beam into bulk transparent material (in particular fused silica) leads to the formation of self-organized micro cavities. The size of the cavities depends on the exposure time, pulse energy and wavelength. High contrast of the refractive index at the boundaries of micro cavities produces spatially variant edge birefringence that can be employed to form birefringent nanostructures inside the bulk transparent material. Such structures allow producing radial/azimuth polarization converters, shown in Fig. 2. Radial/azimuth beam polarization allows focusing laser beam into a tighter spot; additionally, it ensures isotropic laser machining properties when the application is polarization sensitive. It is also applicable in optical tweezers, STED microscopy and other depletion applications. Since the fabrication of macroscopic nanostructure-based optical components, such as radial polarization converters, may well extend over tens of hours, pulse-to-pulse and long term stability of the laser becomes a key factor determining the quality of the process.

3. Volume Bragg grating formation in fused silica

Volume Bragg gratings (VBG) are particular type of phase-gratings embedded in to the volume of transparent material. In comparison with other diffraction gratings, VBG have additional dimension of depth (thickness), which can raise diffraction efficiencies all the way up to the theoretical limit of 100%. Due to this property, VBG are widely used in many photonic applications, mostly in spectroscopic analysis of weak signals, femtosecond pulse compression, telecommunication etc.

VBGs can now be produced in a transparent material by changing its refractive index with ultra-short laser pulses. Photosensitivity previously required for VBG manufacturing is no longer required, thereby widening the range of glasses usable for VBG production. Fused silica (SiO₂) is an attractive candidate because of wide use, commercially accessibility and excellent optical properties.
Direct laser writing of VBG was carried out using second harmonic (515 nm) of *Pharos* laser. The initial Gaussian beam was transformed into Gauss-Bessel (GB) beam using fused silica axicons. Demagnifying telescope was used to decrease the initial size of GB beam by 75 times. Resulted GB beam was imaged into the bulk of the fused silica plate. Diffraction Bragg gratings with efficiencies of \( \sim 90\% \) have been demonstrated. Axial multiplexing of up to \( N = 4 \) layers was necessary to maximize diffraction efficiency. Strongly dispersive gratings with period of 1.5 µm were successfully recorded within 1 h time span over the footprint areas 6×6 mm².

### 4. Processing of hard and brittle materials

Processing of hard and brittle materials such as chemically tempered glass or sapphire is a task that requires special laser sources. *Pharos* features and flexibility ensure precise and reproducible processing process. At the same time, wide choice of processing parameters, allows tailoring the process to the specific application. High peak power and short pulse duration means that *Pharos* laser can be used to cut, drill or mark with minimal thermal damage to the sample.

Sapphire (Al₂O₃) and Silicon Carbide (SiC) dicing technologies are developed for high-brightness/ultra-high-brightness (HB/UHB) LED chip separation. Other similar application is the separation of high power, high frequency device matrixes on SiC substrates. The results of *Pharos* application for industrial hard and brittle materials processing are presented in Fig. 4 (please contact the authors about the details of the laser pulse parameters and focusing optics.).

![Fig. 3](image-url) Left - schematics of the VBG. Several layers (N₁ to Nₙ) of zmax dept gratings are stitched together to form one thick grating with overall thickness \( t \). Right - optical images of fused silica sample with VBGs formed by Gaussian and Gauss-Bessel (GB) ultra short laser pulses at different energies, scanning velocities, and having different grating depths.

![Fig. 4](image-url) Left – edge of sapphire plate (140µm thick) cut at 300mm/sec, single pass (1030nm). Center – edge of sapphire (180µm thick) cut at 300mm/sec, single pass (1030nm). Right – edge of silicon carbide (50µm thick) cut at 300mm/sec, single pass (1030nm). Courtesy of Evana Technologies.

![Fig. 5](image-url) (left) shows an example of tempered glass cut with 1030nm wavelength femtosecond pulses and Fig. 5 (right) shows hole drilling for TGV (through glass via) application performed at Workshop of Photonics using 515nm wavelength pulses. Pulse energies of greater than 0.1 mJ allow cutting tempered glass using just one pass at speed up to 500mm/sec even when glass is up to 0.7 mm thick with 0 - 40 µm deep tempered layers depending on material physical and chemical properties.
Fig. 5. Left – edge of tempered glass cut at 100mm/sec, single pass (1030nm). Right – drilling micro holes in 100 µm thick Shott AF32 glass with second harmonic (515 nm). Courtesy of Workshop of Photonics.

5. Conclusion

Progress in femtosecond laser technology has brought out these state-of-the-art machines from the scientific laboratories into the industrial setting. The author believes that application examples presented in this paper show that flexibility, stability and robustness of femtosecond lasers allow considering them as reliable tools in the areas of nanostructuring and processing of transparent materials for photonics. As the industry embraces this new technology, new fields of application (biomedical, photovoltaic, mechanical engineering) are expected to emerge, ensuring bright future for the femtosecond lasers.

References


