UT Space Institute \textit{ultrafast-laser micromachining workstation}

Housed inside a class 1000 clean room

with two ultrafast laser sources:

- **1.2 W Amplified Femtosecond Laser**
  - Spectra-Physics \textit{Tsunami}
  - Coherent \textit{Verdi-18}
  - Output: 5 \textmu J, 160 fs, 790 nm pulses
  - Repetition rate: single-pulse - 250 KHz

- **20 W Amplitude Systèmes TANGERINE**
  - Output: 100 \textmu J, 325 fs – 10 ps, 1030 nm pulses
  - Repetition rate: single-pulse – 200 kHz – 2 MHz
  - Pulse burst mode: pulses with 10 ns separation
  - SHG option available: 515 nm

Live process monitoring

Video Camera

Microscope

Light Source

Laser beam focusing optics: microscope objective

Work piece clamp

Tilt-Rotation stage

Aerotech XYZ nanostages

PC-LabVIEW workstation control
The Nanofabrication laboratory is a 576 ft$^2$, class 1000 cleanroom for **ultrafast-laser micromachining** and **lithography**. Micromachining operations are supported by two independent laser sources: a **Coherent RegA 9000 Ti:Sapphire amplified femtosecond laser** emitting 5 μJ, 160 fs, 790 nm pulses delivered at rates up to 250 kHz; and a **20 W Amplitude Systèmes TANGERINE laser** emitting 100 μJ, 0.3–10 ps, 1030 nm pulses delivered at rates up to 200 kHz (and 10 μJ pulses at 2 MHz), that can be frequency-doubled by SHG at 515 nm. Both lasers allow pulses to be externally triggered. The TANGERINE also features burst mode, where each pulse burst consists of a train of sub-pulses with 10 ns separations (at 200 kHz, pulse separation is 5 μs).
Two independent laser sources:

- Coherent RegA 9000 Ti:Sapphire amplified femtosecond laser
- and a 20 W Amplitude Systèmes TANGERINE laser.
The laser radiation is focused toward the workpiece using standard optical microscope objectives that produce a typical round Gaussian focus. Microscope objectives with numerical aperture values ranging from 0.2 to 0.8 are available. To expedite certain micromachining operations, the laser radiation can also be shaped into a line focus or a Bessel beam with a long axial depth, using custom optics layouts designed with ZEMAX OpticStudio software.
The Huygens PSF shows >90 % on-axis energy confinement through 500 μm of glass with ~0.6 μm FWHM central lobe diameter.
Laser Machining Methods

Quasi-stationary: pulse duration (~1 ps–10 ns) is much shorter than time to move 1 µm (~1 ms). In essence, only the central lobe of the Bessel beam exceeds the damage threshold, so material modification is highly localized.
Adaptive optics, dynamic laser beam shaping, and dynamic optical aberration correction are accomplished using a **HOLOEYE PLUTO-2-NIR-011 spatial light modulator**, which can operate at both the fundamental IR and SHG wavelengths.

![HOLOEYE PLUTO-2-NIR-011 spatial light modulator.](image)
The workpiece is positioned and moved under the focused laser radiation using a set of nanopositioning stages: one **Aerotech ANT95-3-V single axis lift direct-drive nanopositioning stage**, with 3 mm vertical travel, 200 nm accuracy, 100 nm repeatability, and 1 nm resolution; and one **Aerotech ANT95-50-XY two-axis direct-drive nanopositioning stage**, with 50 mm × 50 mm travel, ±250 nm accuracy, 75 nm repeatability, and 1 nm resolution. An **Aerotech ANT95-360-R single-axis rotary direct-drive nanopositioning stage**, with ±360° continuous rotation angle, 10” accuracy, 1.5” repeatability, and 0.01” resolution is also available for processing workpieces around a rotation axis. The X-axis and Rotation stage also both employ encoders that allow position-synchronized output (PSO) firing of laser pulses, which enables nanometer-scale precision control over complex, custom machining patterns.
Aerotech ANT95-360-R single-axis rotary direct-drive nanopositioning stage:
± 360° continuous rotation angle; 10 arc sec accuracy; 1.5 arc sec repeatability; 0.01 arc sec resolution.

Aerotech ANT95-3-V single-axis lift direct-drive nanopositioning stage:
3 mm vertical travel; 200 nm accuracy; 100 nm repeatability; 1 nm resolution.

Aerotech ANT95-50-XY two-axis direct-drive nanopositioning stages:
50 mm x 50 mm travel; ± 250 nm accuracy; 75 nm repeatability; 1 nm resolution.

Work piece nano-positioning stages

Work piece clamp:
• Wax, vacuum, and also water cavitation mountings available for planar pieces.
• Chucks for pieces with radial symmetry.
The focusing optics are held above the workpiece by a motorized upright microscope that has a digital camera added on. The lasers, the various motion stages, the spatial light modulator, and the digital camera are all computer-controlled using an in-house, customizable virtual instrument (VI) written in National Instruments LabVIEW software. The entire ultrafast-laser micromachining facility sits atop a 5 × 12 × 1.5 ft³ optical table with pneumatic vibration dampers and a stainless-steel top with a rectangular grid of threaded holes.
In-house customizable software control written in LabVIEW.
Some additional equipment in the lab includes the following: a GRENOUILLE (model 8-50-USB by Swamp Optics) for ultrashort pulse-length measurements based on frequency-resolved optical gating; several optical power meters, including a Thorlabs PM100D digital power/energy meter, and Coherent 210 analog and FieldMAX II digital power meters; several fiber-optic spectrometers, including an Ocean Optics QE65000 used in Raman spectroscopy, where a 18 W, 532 nm CW diode-pumped frequency-doubled laser (Nd:YVO4, model Verdi-V18 by Coherent, Inc.) serves as light source; a Mitutoyo stylus and EH-10P gauge for surface height profiling with 0.1 µm resolution; Cole-Parmer Stir-Pak peristaltic pump for water-assisted, cavitation-based laser machining.
Processing work pieces with irregular surfaces

Mitutoyo stylus mapping the surface profile of work piece, prior to laser processing.

The measured surface profile data can be incorporated into the coordinated motion path of the work piece nano-positioning stages, so as to maintain a precise working distance between the focusing optics and the work piece surface, throughout the entire region of interest.
Femtosecond laser micromachining examples

Microfluidic channels patterned on fused silica chips

Example: Passive chemoattractant gradient generator.

Fully assembled microfluidic device housing four chemical concentration gradient generators, as shown in picture on the right. Scale bar: 10 mm.

Optical microscope image of a chemical concentration gradient generator machined on fused silica chip. Inset is a magnified image of upper gradient generating port. Scale bar: 60 um.

in Microscopy and Microanalysis 18, 04, 816-828 (2012)
Femtosecond laser micromachining examples

Subsurface microfluidic channels patterned inside fused silica chips

Example: Cell recruitment device

Cross-sectional representation of water cavitation assisted femtosecond laser machining inside a fused silica chip.

Cell recruitment device housing a single cell recruitment site with three 15 µm diameter chemoattractant delivery ports that stem from a single 4.0 mm long microfluidic channel embedded inside a 200 µm thick fused silica chip.

in Microscopy and Microanalysis 18, 04, 816-828 (2012)
Femtosecond laser micromachining examples

Micropatterned high aspect ratio surface nanopores on fused silica and acrylic

Fused silica chip with over 4 million surface nanopores within 1 cm².

Optical microscope image of fused silica chip surface. Pore spacing = 5 µm.

Typical pore characteristics:
- depth > 10 µm
- OD < 1 µm

SEM image of single surface nanopore.

Polymer replication of nanoporous fused silica and acrylic chips yields arrays of nanofibers.

SEM image of 40-50 µm long HDPE nanofibers. 25° tilt SEM image of 20 µm long NOA60 nanofibers.

Range of materials tested:
- thermoplastics, photocurable resins, solution-castable polymers.

Nanofiber size scales:
- lengths from 1 to 60 µm; length-to-OD aspect ratios up to 200.

Nanofiber density:
- Up to 25 nanofibers per 100 µm². (25 million nanofibers per cm²).
Femtosecond laser micromachining examples

Microscopic marks on metallic surfaces

Stainless steel (SS) rod being laser marked.

Optical microscope image of the laser processed area.

Line width = 10 μm.
Femtosecond laser micromachining examples

SEM image of a curved structure machined on the surface of High-Pressure High-Temperature (HPHT) synthetic single-crystal diamond.


Microscopic pores in metal foils.
Scale bar: 20 um.

Scribed text. Scale bar: 200 um.
Ultrafast-laser micromachining examples

Sketch of microcapillary cross section
- 25 \( \mu \text{m} \)
- 75 \( \mu \text{m} \)
- 200 \( \mu \text{m} \)

Detail of \( \text{SiO}_2 \) chip surface showing 16 laser fabricated microcapillaries

- Plastic cuvette
- Square \( \text{SiO}_2 \) chip
- PDMS gasket
Team

Mr. Alexander Terekhov
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Dr. Brian Canfield
Dr. Lino Costa

Center for Laser Applications
A Tennessee Higher Education Commission Center of Excellence

University of Tennessee Space Institute
List of representative publications

- **Ultrafast laser fabrication of capillary electrospray emitter arrays**, Accepted for publication in the Lasers in Engineering (2020).
- **Responses of transparent dielectrics to Gaussian-focus and Bessel-beam laser machining with single, ultrashort pulses**, in Frontiers in Optics/Laser Science (FiOLS); FTu2C.5; OSA; 2020.
- **High-aspect ratio damage and modification in transparent materials by tailored focusing of femtosecond lasers**, Proceedings SPIE 11173, Laser-induced Damage in Optical Materials 2019, 111730D.
- **Implementation of a turret-mounted optical assembly for femtosecond laser Bessel-beam shaping for machining applications**, Proceedings SPIE 11107, Laser Beam Shaping XIX, 111070A.
- **Ultrathin Polymer Membranes with Patterned, Micrometric Pores for Organs-on-Chips**, ACS applied materials & interfaces 8, 34, 22629-22636 (2016).
List of representative publications

• Solution-cast high-aspect-ratio polymer structures from direct-write templates, ACS Applied Materials & Interfaces 5, 1, 1-5 (2013).
• On-Chip Open Microfluidic Devices for Chemotaxis Studies, Microscopy and Microanalysis 18, 04, 816-828 (2012).
• On femtosecond micromachining of HPHT single-crystal diamond with direct laser writing using tight focusing, Optics express 18, 12, 13122-13135 (2010).
• Single-pulse ultrafast-laser machining of high aspect nano-holes at the surface of SiO₂, Optics Express 16, 19, 14411-14420 (2008).