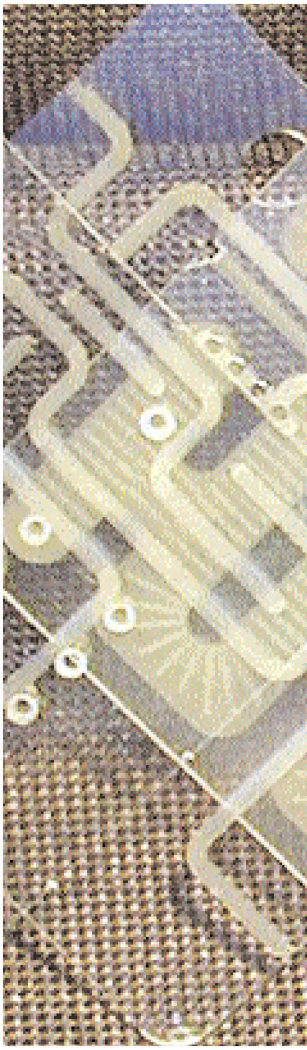
Laser Fabrication of Glass Microstructures

FEATURE

by William Hansen, Pete Fuqua, Frank Livingston, Adam Huang, Meg Abraham, Dave Taylor, Siegfried Janson, and Henry Helvajian



One can make a strong argument that some high-tech industries have entered the Age of Glass. Two growing market forces support this claim. The ever-expanding communications industry is driven to increase bandwidth and, thereby, to use photonics and glass materials, and the emerging microbioinstrumentation industry would prefer glass to other substrates because of its inert and well-characterized properties. This raises the question of whether adequate glass-microfabrication techniques exist to meet the expected demand for miniaturization and systems integration.

The fabrication of intricate microstructures in or on glass materials is considered a necessary value-added component in the development of advanced photonics and certain microinstruments. In photonic applications, for example, microstructure patterns can be used to guide light or serve as frequency selectors. In biochemical applications, microstructure patterns can control fluidic flow or the slicing and dicing of cells to capture the genetic material inside them.

For the past seven years, researchers at The Aerospace Corporation (El Segundo, CA), a Department of Defense contract research center, have explored the potential for microfabricating a unique class of glass materials, called photocerams, using an innovative ultraviolet (UV) laser-processing technique. This technology promises a more precise, less expensive way of creating intricate glass microstructures. To date, we have created many such structures and assembled an experimental picosatellite made almost entirely of glass that weighs only 100g. Our goal is to develop a competitive technology for industry that will advance the current state of microfabrication.

The laser is the one materials-processing tool that can remove, add, and alter matter with site-specific control. Applying laser-spectroscopic techniques further enables the use of lasers as in situ probes for process control or as surface monitors with selective vision. Yet, historically, lasers have made only marginal inroads into industrial processing because of the cost of running and maintaining them, and because of their inefficiency in terms of area of material affected per unit cost. Laser processing has been used only in applications where there is a clear value-added component.

Figure 1. Optical microscopic picture of a dual counter-rotating turbine structure 1 cm in diameter and 1 mm thick, manufactured by laser from a photoceramic material.

However, lasers today are more reliable and user-friendly, and less expensive to operate and maintain, than those of five years ago. With these advances have come a fundamental shift in thinking and the development of high-average-power lasers specifically designed for materials processing in industry. One example is the free-electron laser (FEL) at the Thomas Jefferson National Accelerator Facility, known as the Jefferson Laboratory, in Newport News, Virginia (see *The Industrial Physicist*, April/May 2002, pp. 24–25).

Making microstructures

Microstructure patterns can be fashioned by lithographic and chemical-etching techniques, but these approaches are primarily limited to the fabrication of two-dimensional patterns or structures such as open trenches. Laser-based techniques can add nuance to these fabrication approaches and, thereby, permit the development of more complex microstructures with variegated aspect ratios.

There are two general approaches to the laser microfabrication of glass materials. The first uses a laser as the light source in photolithography. Variants of this technique include moving the mask, the workpiece, or both in synchronous fashion to generate complex patterns. The second approach, called direct-write processing, aims the laser beam onto the workpiece and "writes" the pattern using XYZ-galvanometer or stepper-motion controls. Because masks do not encumber this serial processing technique, it provides for rapid prototyping and the fabrication of true three-dimensional structures.

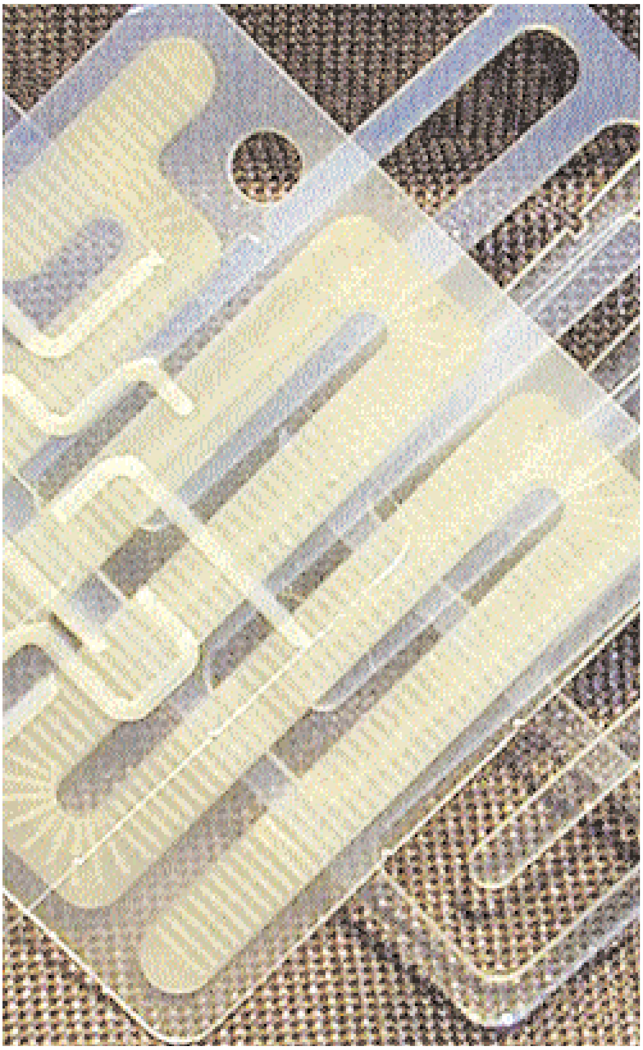


Figure 2. These seven glass wafers are patterned and etched. Measuring 50 × 50 × 1 mm, they will be fused to make up the body of a 100-g co-orbiting satellite assistant.

In both laser approaches, microscopic imaging permits the fabrication of microstructures with resolution approaching the wavelength of the light. One can breach this resolution limit by applying interferometric techniques or near-field optics, if additional system complexity can be accommodated. In the microfabrication of glass, the lithographic approach uses UV (248- or 193-nm wavelength) or vacuum UV (157 nm) excimer lasers. The direct-write approach attains its best results with a solid-state, femtosecond pulse-width laser.

A third approach, developed at The Aerospace Corporation and dubbed laser-photoactivated processing, merges the advantages of lithographic batch processing—speed, process uniformity, and cost effectiveness—with the flexibility of direct-write processing, namely rapid prototyping and true three-dimensional fabrication. In this merged-processing approach, the material itself *must* play a role. The technique relies on photocerams, engineered glass materials that are made photosensitive by dopants that cause exposed areas to become susceptible to chemical etching. The process is akin to the way photoresist material is used in photolithography except that the substrate material itself is designed with a selective etching attribute.

In this approach, the laser photons are only used for the patterning step and the laser energy is delivered via direct-write. The final step uses a chemical agent to remove the exposed material in toto by batch processing. With this approach, three-dimensional pattern exposures are possible without sacrificing overall fabrication throughput. When evaluated as a whole, laser-photoactivated processing can be more cost-effective than the other two laser techniques because the time-consuming material-removal step is relegated to a batch process.

Photocerams

Photocerams are particularly amenable to laser-photoactivated processing because they have controlled devitrification. That is, exposure to light, typically UV radiation, begins a process that changes the material from a glassy state to a crystalline ceramic state. A baking step follows the patterned exposure, which induces crystalline growth in the exposed areas. Finally, material is removed using a 5% solution of hydrofluoric acid (HF). The crystalline phase is roughly 30 times more soluble in HF than the unexposed glass. Photocerams emerged in the late 1940s as a viable industrial material, and their most renowned use is in making the home dishware sold under the name Corning Ware.

The Aerospace Corporation's investigation of photocerams has focused on a particular formulation of the material that is pore-free, chemically stable, transparent from near-UV to near-IR wavelengths, and biocompatible. We primarily work with Foturan, made by the Schott Group (Mainz Weisenau, Germany), one of two high-grade photocerams commercially available. Hoya Corp. (Tokyo, Japan) makes a competing product called PEG-3, which we have also used in experiments.

Five years ago, we discovered to our surprise that the UV pulsed-laser technique can pattern photocerams at a wavelength that is outside the traditional processing range of the material. We hypothesized that a nonlinear absorption process was operative in the photoelectron excitation process because our UV laser delivers its energy in 7-ns bursts, whereas UV lamps, the traditional tools, illuminate a target continuously. To test this hypothesis, we examined the sensitivity of Foturan and PEG-3 using the picosecond pulses of the FEL at the Jefferson Laboratory. Those experiments indicated that when FELs reach the factory floor, industry will have a powerful new tool to etch intricate glass microstructures.

At least two other research groups are working on the laser processing of photocerams. One is a collaboration involving researchers at the Fraunhofer Institute for Laser Technology and the Rheinisch-Westfälische Technical University, both in Aachen, Germany. This effort is focused on developing photoceram glasses and investigating their photoexposure properties. A group at the Institute of Physical and Chemical Research (Wako-Saitama, Japan) is looking at the laser material processing of the commercially available photocerams. That team recently exposed Foturan using a femtosecond pulse laser operating at 755 nm, which is far above the expected absorption peak at ~318 nm.

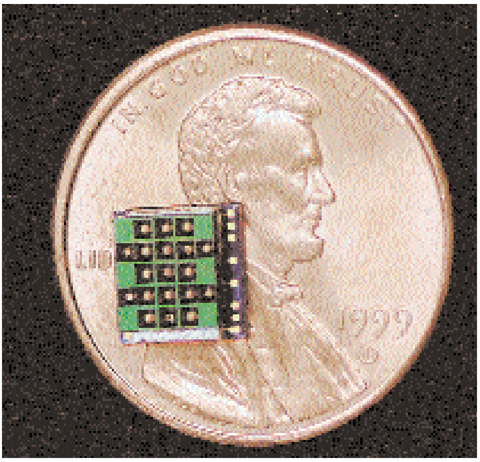


Figure 3. An array of digitally addressable microthrusters, shown against a penny, is used to maintain attitude control of a nanosatellite and includes a middle glass-ceramic layer.

Laser exposure

Our photoceram-processing technique uses multiple UV wavelengths from kilohertz-repetition-rate pulsed lasers to volumetrically pattern the photoceram wafers via direct-write processing. The use of multiple laser wavelengths, from 248 to 355 nm, permits varying the penetration depth of the laser light and determines the effective height of the microstructure being patterned. Throughout an exposure, the laser beam remains stationary and the photoceram is moved to produce the desired pattern. In processing an embedded microstructure, such as a channel, small openings or “vias” are included in the patterning to allow the etching solution to enter the material’s interior and flush out the waste products. To implement this laser direct-write patterning, a computer-controlled XYZ microstepper has been integrated with an optical-control system that has the following features:

- Pattern design and implementation are controlled by standard CAD–CAM software.
- Input wavelengths are automatically selected from several laser sources according to the desired pattern.
- Incident laser fluence (energy per unit area) and the applied dose (a product of the number of laser pulses and the fluence) are controlled and can be varied during the exposure. By controlling the color, dose, and where the energy is deposited, we can make three-dimensional structures and embedded features, such as tunnels.
- The laser beam shape at the focal volume and the depth of focus are also controlled.

By applying these controls, we ensure against thermal runaway damage, a destructive phenomenon caused by the focused laser beam that can induce material stress and fracture. These controls also permit precision exposure at a particular depth. We have measured the operational parameters, or processing window, for our technique and have used the data to fabricate three-dimensional structures that have appeal to both the photonic and microinstrumentation industries.

Microstructures can be fabricated to operate either as solitary units, in large arrays, or as an interconnected pattern of assemblies that function as a complex microdevice. Indeed, we have fabricated microcomponents that are large (centimeter scale, but with microscopic relief) and freestanding to an extent, which can be made to move. Other examples include structures on the order of 50 μm that have aspect ratios greater than 10, structures that are undercut, and embedded features, such as patterned channels within a 3-mm-thick wafer. Embedded channels have many applications, such as in connecting adjacent fluidic reservoirs without incurring an expensive package-sealing step.

It is possible to fabricate more articulate structures with the technique. Figure 1 shows a miniature dual-bearing turbine (1 cm in diameter × 1 mm thick) in a photoceram material that has been fashioned much like cut-crystal stemware. The facets at the center of the turbine are roughly 50 μm; the turbine blades are more than 300 μm high and taper down to nearly 10 μm at their thinnest point.

Tiny satellites

Laser-photoactivated processing has also been used to microengineer several prototype subsystems for the development of mass-producible miniature satellites that weigh less than 1 kg, which are called nanosatellites. For example, several microthruster designs have been fabricated to maintain attitude control of a nanosatellite. The microthruster impulse and thrust efficiency have been experimentally measured, and one design successfully flew on the Space Shuttle in July 1999 (Figure 3). The goal was to test the microthruster’s ability to survive a launch.

We have also fabricated a seven-glass wafer sandwich unit that is interconnected with a complex, three-dimensional, fluidic-channel system that serves as the fuel tank, plenum, and fuel delivery system for an integrated six-thruster satellite, which with electronics, battery, and fuel weighs a little more than 100 g. This picosatellite, called the Co-Orbiting Satellite Assistant (COSA), is 50 × 50 × 50 mm and is intended to assist a larger mother ship, such as the Space Shuttle or International Space Station, by providing an external set of free-flying sensors. The seven glass patterned wafers are shown in Figure 2. Missing are a set of thin batteries and an eighth wafer—which can be patterned into silicon—that contains the electronics. The whole unit can be stacked and bonded together.

COSA is a limited-mission satellite, and this particular design carries only 5 cm^2 of onboard fuel, such as butane or ammonia. Communication with COSA is conducted via the mother ship while the tiny craft conducts operations in space. After completion of its mission, an orbit-descent thruster is ignited to drive the COSA satellite into a controlled Earth reentry and burn-up in the atmosphere.

COSA-type satellites are intended to troubleshoot problems encountered by its mother ship during spaceflight, such as an antenna that fails to deploy or the loss of vital heat-resistant tiles covering the Space Shuttle that might need to be replaced in orbit. Several of the craft would be stored and released when needed. Using its tiny thrusters, a COSA would slowly circle its host spacecraft at a distance of 50 to 100 m, and its sensors would send data or photographs to the mother ship, which would retransmit the information to ground controllers to aid in diagnosing and fixing the problem.

A final comment. The laser-photoactivated, volumetric-exposure technique is a nonthermal excitation process, which uses laser photon energy to excite an electronic state of a photoactive dopant. Because the excitation process produces negligible heat, it is potentially scalable to higher "writing" speeds and higher laser powers or repetition rates. As a result, such processes would strongly benefit from a light source such as the Jefferson Laboratory's FEL, where megahertz repetition rates and kilowatt average powers are now available.

Further reading

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BIOGRAPHY

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