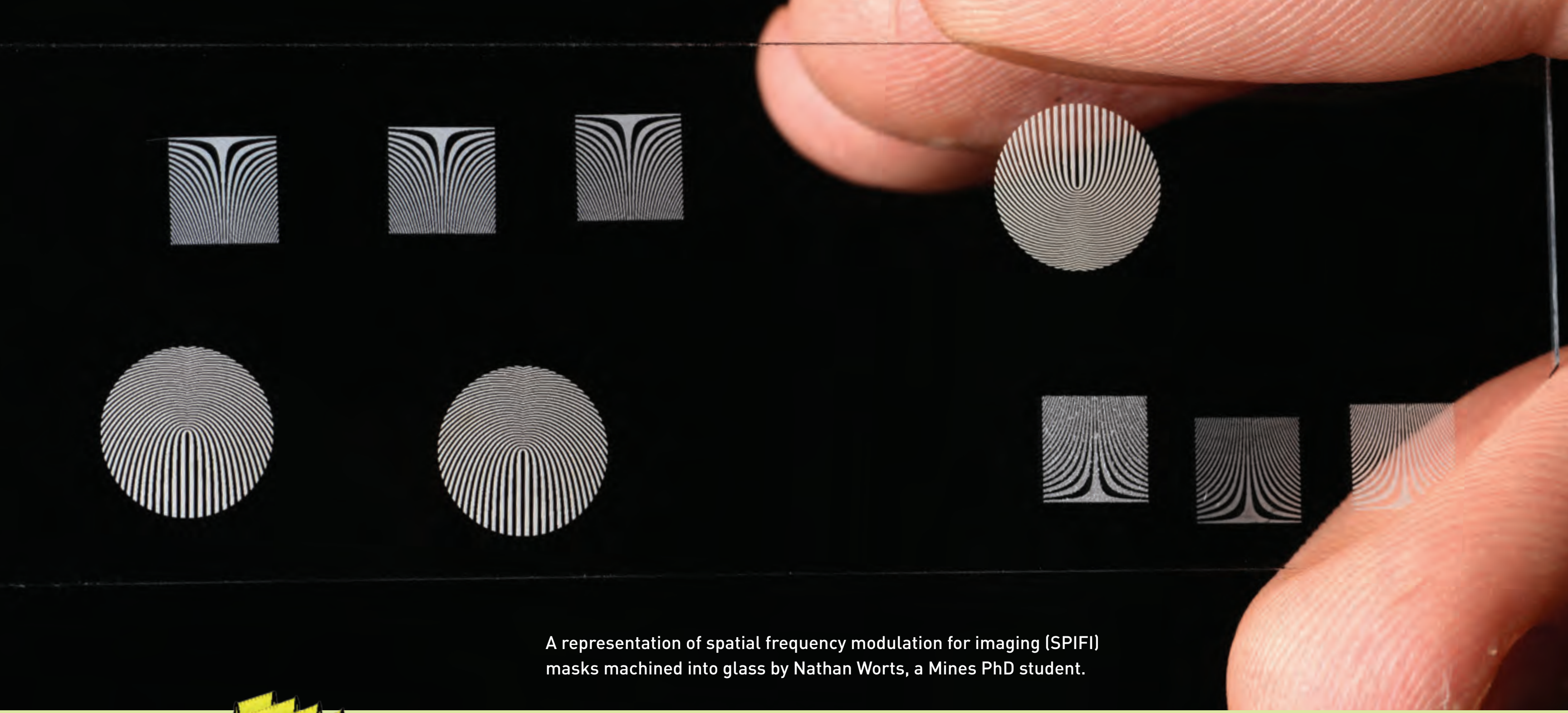
Seeing as machining

A single team in the basement of the Mines General Research Laboratory has advanced the state of the art in what might seem two very different realms: machine tools and microscopes

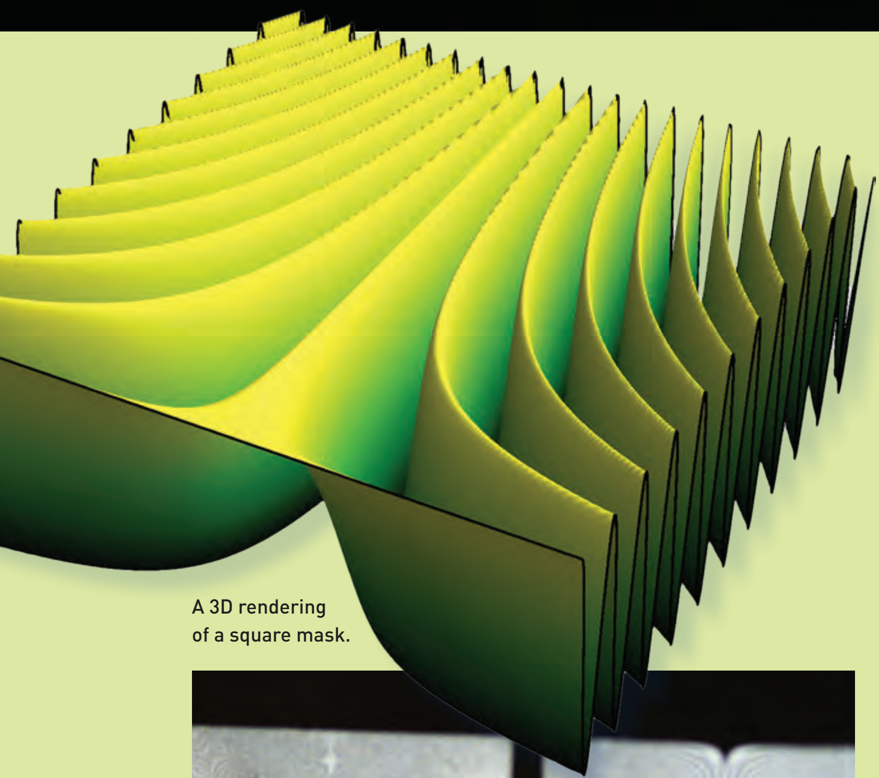
These aren't your typical saws, lathes and presses—and it's far from your average microscope. Jeff Squier and his team do their machining with lasers, and they have combined a microscope of their own design into a single system that promises to improve everything from eye surgery to 3D printing, and at the tiniest scales.

Squier, a Mines professor and chair of the Department of Physics, leads a group whose system combines ultrafast-laser micromachining with microscopy capable of observing and guiding the laser's work in real time. They have broken new ground in both disciplines to enable a unified system capable of cutting, shaping and transforming across a wide range of dimensions deep inside translucent materials while observing and guiding the process.

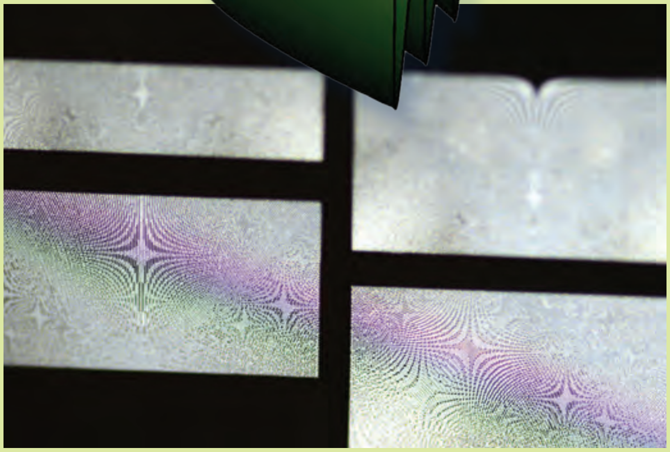
"We're combining the imaging with the machining for the first time," Squier said. "That's really powerful."



A representation of spatial frequency modulation for imaging (SPIFI) masks machined into glass by Nathan Worts, a Mines PhD student.



A 3D rendering of a square mask.



Although it's built on a technological foundation Squier has been pioneering since the late 1980s, the system hinges on two innovations, each the topic of a 2015 Mines PhD dissertation. The first is simultaneous spatial and temporal focusing (SSTF) of the ultrafast laser. The second is spatial frequency modulation for imaging (SPIFI) on the microscope side.

SSTF is a twist on the chirped-pulse amplification (CPA) systems Squier has advanced for decades. Such systems use a series of lenses, gratings, amplifiers, compressors and other optical hardware to stretch out and then recompress femtosecond laser pulses in ways that enable them to machine, ablate or transform targets at submicron scales. (A strand of human hair is about 30 microns in diameter; 100 femtoseconds is about how long it takes light to travel that distance.) Current applications include machining optical waveguides or diffraction gratings, making biomedical stents, carving microfluidic channels and ablating thin films for displays or solar applications.

The CPA-based manipulation of laser pulses is critical because femtosecond lasers squeeze so much energy into their pulses that amplifying them directly would damage the system itself.

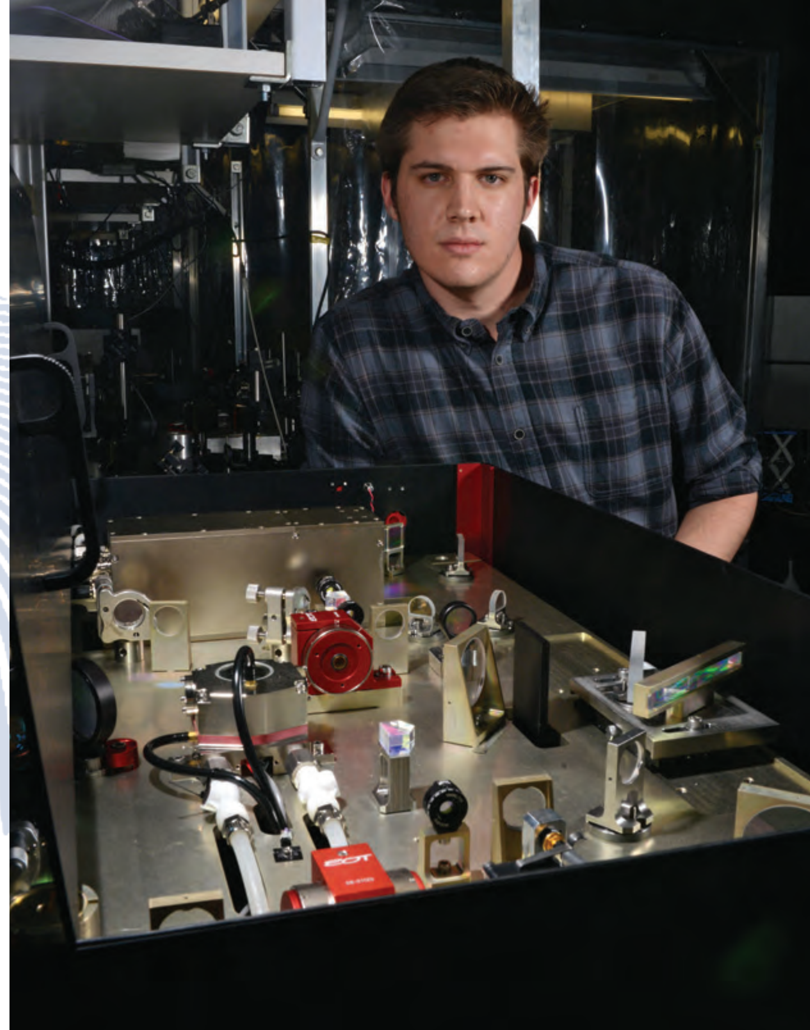
"Peak power goes up so fast, you'd literally just drill holes in everything," Squier said.

But even with CPA, ultrafast laser machining has been limited by its own power. These lasers damage everything between the final aperture and the ultimate target. There are many cases—eye surgery, for example, or etching optics deep inside glass—where this would be detrimental. SSTF is a solution.

Erica Block, now a postdoctoral researcher at Mines, spent years working with Squier to develop SSTF, which was the basis of her dissertation. The basic principle is familiar to anyone who has focused sunlight with a magnifying glass. Close to the glass, the light remains diffuse; at the focal point, its white-hot confluence burns holes in leaves.

While a great deal more complicated, SSTF works by the same principle, using a lens to focus different laser wavelengths such that they overlap again precisely at the focal point. Rather than burning

> "SPIFI will never match the resolution of an electron microscope, Young says. But electron microscopes are killers; SPIFI can function harmlessly in a human eye."



Mines PhD student Nathan Worts sits behind a KMLabs laser.

a channel all the way to the target, one can carve, ablate, etch and machine 3D shapes into the core while keeping the periphery pristine. Classic femtosecond-laser micromachining can have no such lens because, as Squier put it, "the laser beam would machine the lens."

SSTF's incorporation of this lens opened the door to integrating a laser microscope with the micromachining system. Michael Young defended his Mines PhD on the microscopy technique he developed to exploit the SSTF lens the week after Block defended hers. Rather than photos of the microscope itself, which occupies a Mines GRL lab next door to the one hosting the SSTF system, his dissertation's cover slide featured a vintage fighter jet loaded with missiles.

"Back in the late 1960s and 1970s, the technology that they had at the head of those heat-seeking missiles is the technology we use to make an image," said Young, now a postdoctoral research fellow on Squier's team.

Well, sort of. Young's SPIFI system starts out using the same femtosecond laser source as the SSTF's machining setup, but in Young's case, it's an engine for wide-field two-photon excitation fluorescence (TPEF) microscopy, to which he added a feature based on, but decades more advanced than, the old heat-seeking missile technology.

Young started work on the first version soon after earning his Mines undergraduate degree in December 2008. He faced the challenge of building a microscope capable of observation at different machining depths, at a high frame rate and at adequate resolution. Young came up with a system featuring a single-pixel sensor and a spatial light modulator—a striped mask called a frequency-modulation reticle, like the ones that spun in the center of missiles.

In this case, the mask was digital, a spatial light modulator built by Boulder Nonlinear Systems, which is supporting Young's fellowship. Light falls on the single pixel differently depending on where it passes through the mask, less on the outside, more in the center. In the ballistic manifestation, the rocket steered toward the light. The microscope uses it to help paint a picture. The image can be centimeters wide—Young has a high-res SPIFI copy of his daughter—or it can be a micron wide. SPIFI will never match the resolution of an electron microscope, Young says. But electron microscopes are killers; SPIFI can function harmlessly in a human eye.

Mines PhD student Nathan Worts is now working to advance Block's micromachining system using an SSTF that KMLabs of Boulder, Colorado, built (the company has also licensed the technology). It compresses a research system occupying dozens of square feet into a box the size of a large suitcase. Meanwhile, Young is enhancing the microscope's resolution with new lenses and other off-the-shelf components. It's a marriage that Squier expects to be fruitful.

"The spatial scales we can address, the broad number of materials we can address, and the fact that we're looking at surgical tools and 3D prototyping—the application base is huge," he said.