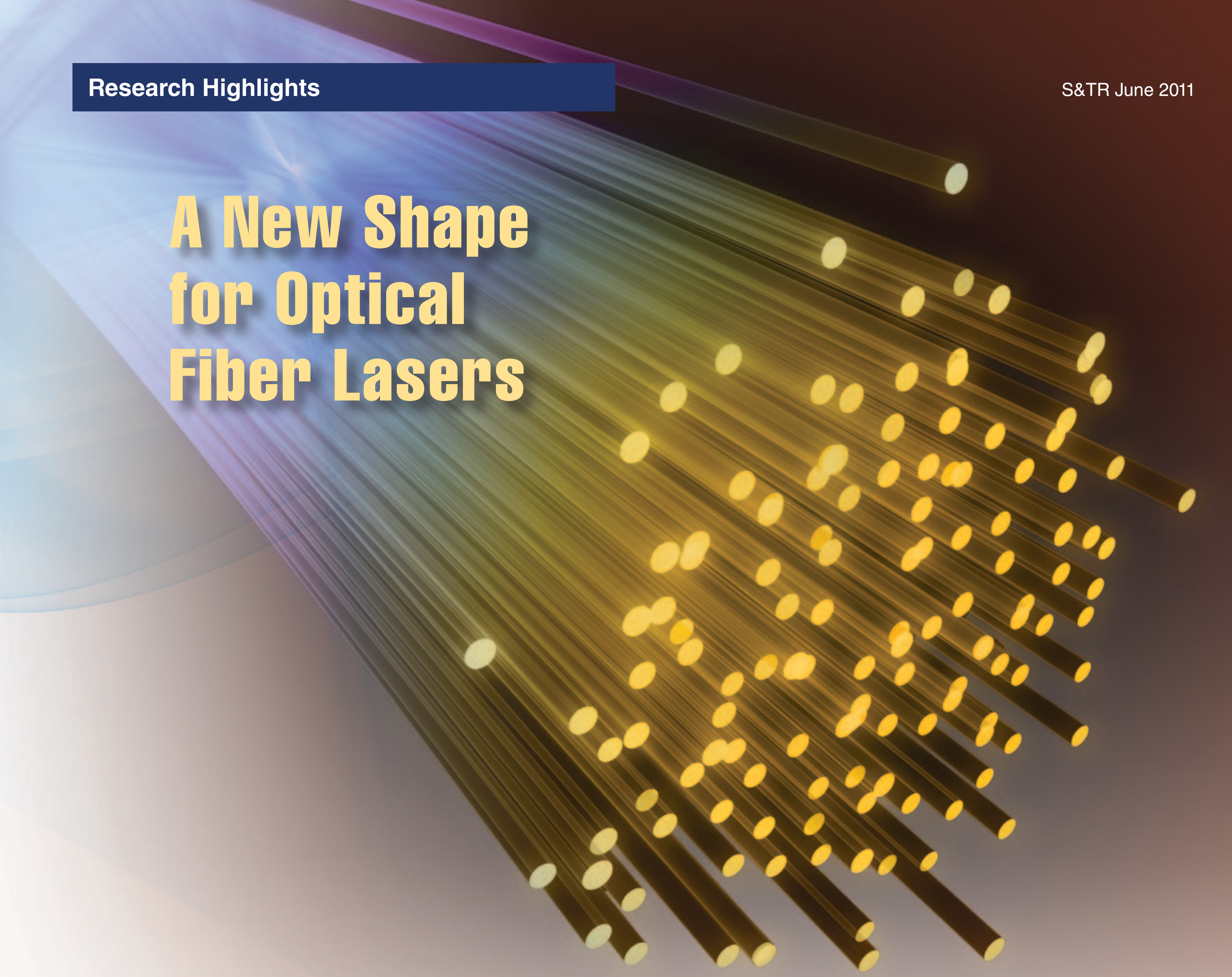
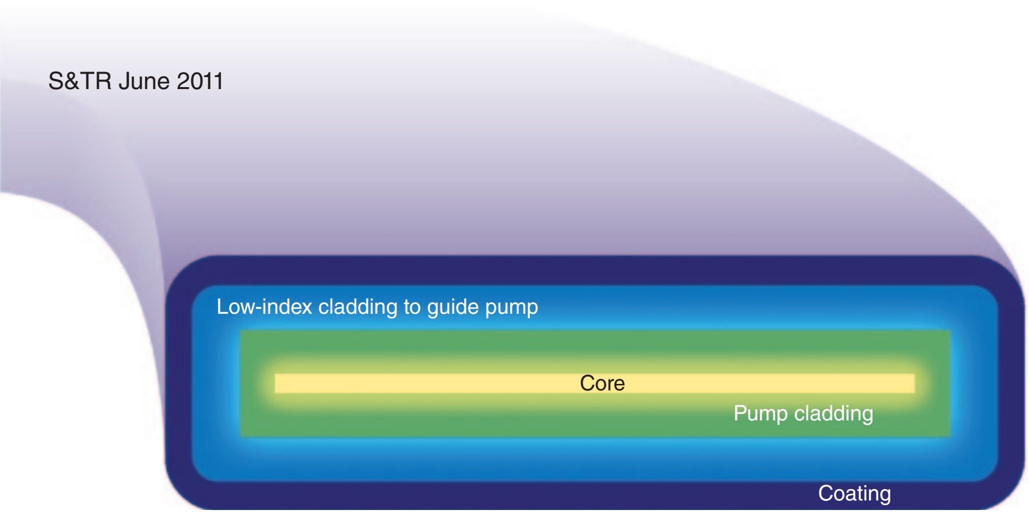


A New Shape for Optical Fiber Lasers

FIRST developed in the 1970s, thin, flexible, and transparent optical fiber revolutionized the telecommunications industry, acting as the structure for carrying electromagnetic waves from point to point. Because of its large bandwidth and immunity from electromagnetic interference, optical fiber has largely replaced copper wire for transmitting data over long distances—across the country, for example.

An optical fiber can also be made into a laser by mixing rare-earth ions into the fiber's glass structure and pumping those ions with a separate laser diode, such as the diodes that generate the light in a laser pointer. Fiber lasers can take this concept a step further, combining the power of many inexpensive laser diodes into a single coherent beam. The fibers are especially well suited for scaling up high-power, continuous-wave lasers that emit a steady stream of photons. Commercial laser systems have reached average powers of 10 kilowatts, high enough to cut and machine metal parts for the automotive and heavy-equipment industries.

Because fiber lasers are compact and reliable and their beams can be focused to extremely small, diffraction-limited spots, they have also found a niche in scientific applications. In this area, however, their performance is limited. They work well for tasks in which energy is spread evenly over time—the metaphorical equivalent of slowly pushing a tack into a board with your thumb—but not for applications that require energy bursts—akin to hitting a nail with a hammer. That's because the fiber's small cross section lets it amplify pulses to levels that damage the fiber itself.



The ribbon-shaped optical fiber being developed at Livermore has a wider cross section than the traditional round fibers used by the telecommunications industry.

Computational modeling at Livermore suggests that fiber lasers cannot generate more than 30 to 40 kilowatts of power—about 10 million times the power of a typical laser pointer. While this output is more than enough to cut intricate patterns into blocks of steel, it falls short by a factor of 100 of the power needed for alternative-energy schemes the Laboratory is pursuing.

Attempts to exceed the fundamental limit using round optical fiber lead to damaging nonlinear and thermal effects. One such effect is thermal lensing, during which the beam intensifies as it amps up, focuses, and then damages the fiber. Another is stimulated Raman scattering, in which power is lost as it is being extracted. Raman scattering describes the inelastic scattering of a photon that creates or annihilates an optical phonon.

Research groups worldwide are working to surpass this limit with existing fiber lasers, but most of them are extending fabrication techniques developed for the telecommunications industry. By departing from that approach, a multidisciplinary team led by Livermore physicists Jay Dawson and Mike Messerly has been inspired to change the structure of optical fiber to create light that is compact, reliable, and efficient.

The team's studies show that the root of the fundamental limit lies in the fibers' round structure. "We can't get the needed output with the basic circular geometry," says Dawson. "Instead, we've stepped back to reexamine all of the factors that prevent scaling further." In addition to Dawson and Messerly, the team includes Arun Sridharan, Amber Bullington, Graham Allen, Craig Siders, Ray Beach, Regina Bonanno, and Chris Barty, all from the National Ignition Facility (NIF) and Photon Science Principal Directorate, as well as Paul Pax, John Heebner, and Henry Phan from the Engineering Directorate.

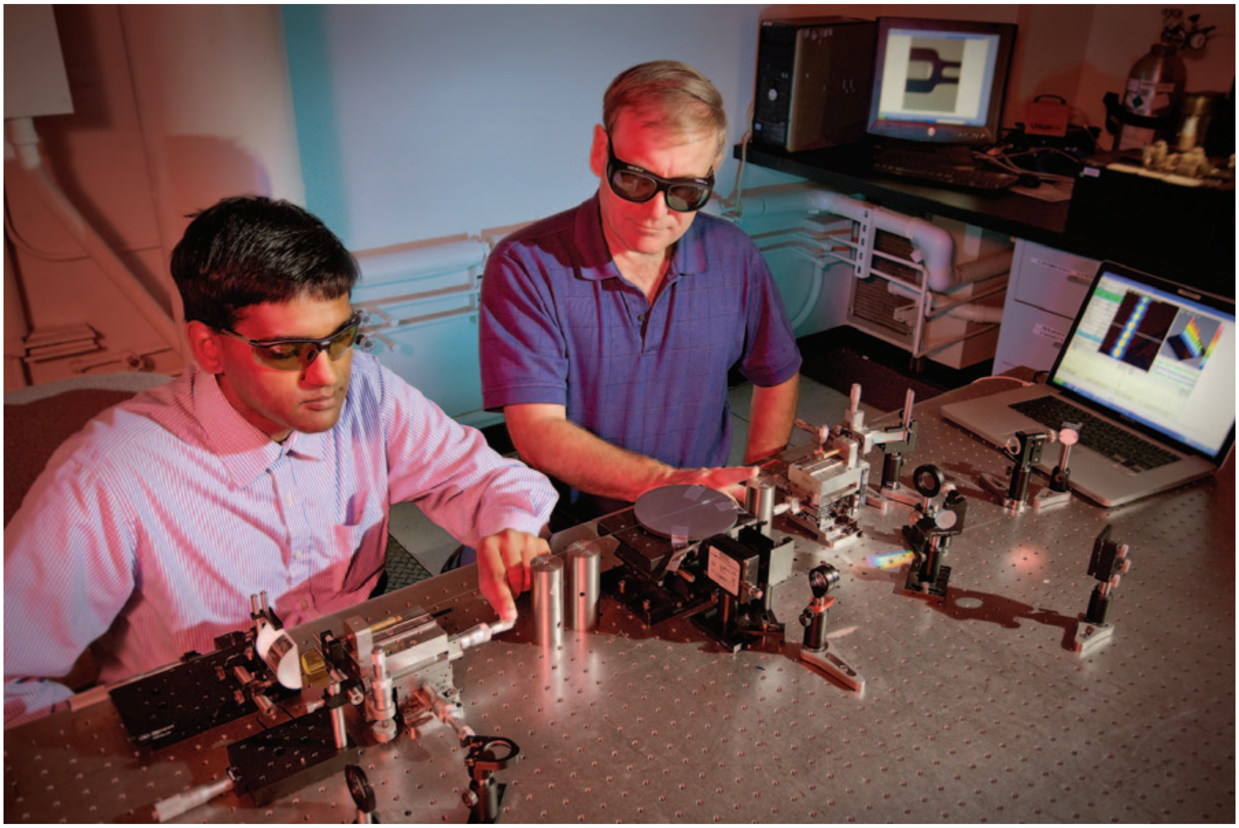
Current industrial-grade fiber lasers tend to produce beams with diameters of a few tens of micrometers at a distance of 1 meter. Diffraction-limited or "single-mode" fiber lasers designed with a focusing optic can produce comparably sized beams at a distance of 1 kilometer. These lasers offer excellent efficiency in converting electricity to highly directional photons, plus they are easy to use and have a wide range of operating wavelengths. The key to scaling to higher powers and pulse energies lies in solving the technical challenges associated with fabricating a ribbonlike fiber.

Light Bending

Beach was the first to publish the concept and construction of a ribbonlike fiber. "The analogy is not perfect," says Messerly, "but the comparison helps illustrate the difference between the two structures. In traditional round fiber, light doesn't stay guided when the fiber is bent. It's like trying to bend an aluminum bar. Ribbon fibers spread that bar into a sheet, like aluminum foil, a smarter geometry for bending." The ribbonlike structure can be bent along the thin axis, and because of its width, it can still carry lots of power.

With funding from the Laboratory Directed Research and Development Program, the Livermore team is not only creating a comprehensive model of the ribbon-fiber structure, or waveguide, but also is developing new fabrication techniques. They will then construct and test a pulsed laser system demonstrating all the critical physics for a ribbon fiber that can scale beyond 30 kilowatts and a few millijoules.

"Our goal is to develop ribbon fiber lasers that can amplify light beams to powers well beyond the fundamental limits," says Heebner. "Accomplishing this goal would make fiber lasers competitive with traditional solid-state lasers and introduce many advantages—compact geometries, robust alignment, and improved thermal management to name a few." To access the higher powers, the team is designing the ribbon-fiber structure so that it preserves beam quality. "Although the highest order mode is predicted to be the most robust while in the amplifier, it is beneficial to inject and extract light in the fundamental mode so it can be easily reshaped into a clean output beam," Heebner says. "We are exploring a number of methods for converting the beam between these modes. Doing this will enable high-average-power light extraction with high beam quality." If successful, these compact, high-average-power light sources will facilitate new applications such as extreme ultraviolet sources, laser machining, and advanced materials processing.



Livermore scientists (left) Arun Sridharan and (right) Jay Dawson couple laser light into a higher order mode of a rectangular core optical fiber.

More Than a Model

The team is constructing an 8-meter-tall tower for "drawing," or fabricating, various optical fiber structures on demand. Dawson says, "During the earlier research, Beach and his team had no fabrication capability, and their vendors needed almost two years to produce a sample fiber. In that time, we'll have completed the draw tower, giving us the capability to fabricate these fibers onsite." Dawson is encouraged by what's proving possible. "When Mike [Messerly] took a weeklong course at the University of Bath, he and a fellow student fabricated a complex structure in their first few days."

For nearly a decade, the Livermore group has been working on fiber laser systems for robust injection-seed systems for high-energy lasers such as NIF's Advanced Radiographic Capability (see *S&TR*, December 2010, pp. 12–18), monoenergetic gamma-ray source (see *S&TR*, April/May 2011, pp. 15–17), and Mercury laser system. The team is strengthened by its multidisciplinary nature, providing expertise in computer modeling, beam propagation, thermal effects, and material processing of glass as well as laser physics, optics, and engineering. The research also benefits from collaborations with the University of Southampton, the University of Michigan, and the Air Force Academy. Dawson says, "As a national lab, we can often take more risks than a private company that has to turn a profit quickly, giving us the time to evaluate new design options."

The project's ultimate goal is to achieve a full-physics demonstration of a ribbon-fiber amplifier, which will lead to future research opportunities. The team will also make the technology available to other Department of Energy laboratories and for industrial and defense applications. The researchers believe that industry will recognize the benefits of the path they've taken and, once the concept is proven, will make prudent infrastructure investments. Success could mean that next-generation concepts for laser-based particle accelerators—something only talked about today—could be realized.

—Kris Fury

Key Words: optical fiber, ribbon-fiber laser.

For further information contact Jay Dawson (925) 422-1617 (dawson17@llnl.gov).