High-Power Fiber Lasers
Johan Nilsson, *et al.*
Science **332**, 921 (2011);
DOI: 10.1126/science.1194863

PHYSICS

High-Power Fiber Lasers

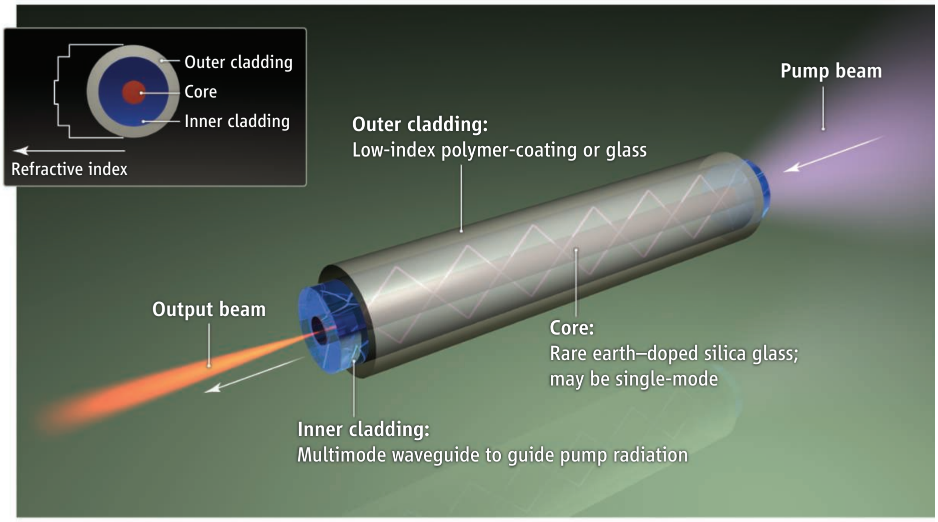
The brightness, robustness, and flexibility of high-power fiber laser sources provide an enabling technology for science and industry.

Johan Nilsson and David N. Payne

Lasers are used in a wide range of applications that benefit from the pin-sharp (spatially coherent) beam and immense pulse peak power they can provide. In many cases, notably manufacturing, high average power is essential for cutting, welding, and drilling. The low-power optical fiber amplifier (*1*), acclaimed as the mainstay of the fiber-based Internet, can be massively scaled to emerge as an industrial laser frontrunner, reaching an output power of >1 kW (*2*) and, more recently, an astounding 10 kW (*3*). These results were obtained with (nearly) diffraction-limited beam quality, which determines the ability to focus to a tight spot. Together with the power and wavelength, it determines the spatial brightness, or radiance. The brightness is exceptionally high for these fiber lasers, and this, rather than the power itself, determines the power density achievable on a target.

There are several "secrets" behind the success of high-power fiber lasers. One is cladding-pumping (*4–6*), which uses a more sophisticated fiber structure than that of a conventional optical fiber (see the figure). In addition to the usual few-micrometer-sized core for guiding the light, these double-clad fibers include a second, coaxial, waveguide that surrounds the core. Most fiber lasers are optically pumped by semiconductor laser diodes, and the large size of this second waveguide allows pumping with numerous pump diodes that provide several kilowatts of low-cost, low-brightness optical power.

Then there is the incorporation into the core of ytterbium as the laser-active (amplifying) dopant. Ytterbium is a very efficient laser ion, partly due to the proximity of the wavelength of the amplified light (typically 1040 to 1100 nm) to that of the pump (typically 910 to 980 nm) (*7*, *8*). The difference is called the "quantum defect" and determines the amount of surplus heat a laser will produce; to minimize this, a pump wavelength of 1020 nm was used for the 10-kW demonstration (*3*). The optical conversion efficiency of a fiber laser can exceed 80%, at an electrical-to-optical conversion of 40%. Furthermore, ytterbium can be incorporated in concentrations as high as several percent so that practical fiber laser lengths of a few meters can absorb the pump light. An early enabling commercial breakthrough was the development of new silica-based glass hosts that allow for high ytterbium concentrations without the photodarkening from which many silica hosts suffer. Beside ytterbium, erbium and thulium are used for wavelengths around 1.6 and 2 μm, respectively, reaching powers of about 0.3 and 1 kW makes it possible to reach this optimal ratio, whereas in a bulk laser the inevitable diffraction can make the ratio orders of magnitudes smaller than optimal. The right ratio is, however, not sufficient. It is also necessary to have a large core to keep the power density below the damage threshold and improve the energy storage, in case of high-energy pulses. There are limits to the core diameter in a fiber laser before the beam quality degrades and the guidance becomes too weak, which causes



Fiber lasing. Schematic of a double-clad fiber laser in an end-pumped configuration (not to scale).

A prime attraction of fiber waveguiding lasers over their conventional optically pumped "bulk" laser cousins is thermal management. A host of thermal gremlins have plagued bulk lasers over the years, from catastrophic fracture to thermal beam distortions that degrade the beam quality, thus limiting the brightness. By contrast, the long fiber laser is made from refractory silica and has a hair-thin active region from which it is easy to extract heat. The reduced thermal load per unit length lowers the thermally induced refractive-index distortions and, furthermore, a guided laser mode can maintain an unperturbed, flat wavefront even in the presence of such distortions.

There is, however, a drawback in having a long and thin gain medium—nonlinear optical degradation. There is an optimal ratio of the length of the gain medium to the cross-sectional area that best balances thermal and nonlinear degradation (*8*). Waveguiding

problems with bend loss and packaging. This occurs in the 50- to 100-μm region, although the cores in commerical single-mode devices are seldom larger than 30 μm.

Thanks to the trade-off between thermal and nonlinear limits, the impressive progress in core area scaling, and the superb properties of ytterbium-doped silica, fiber lasers excel as high-power, high-brightness laser sources. Equally important for their commercial success is the integration of all-fiber components to make a monolithic guided-wave laser that resists environmental abuse. However, fiber lasers are in their infancy, and this is only the beginning of the story. High-power fibers are often configured as amplifiers rather than as "pure" lasers (*8*). Fibers work very well as amplifiers with an unsurpassed ability to combine high gain, high power, and high efficiency. It is therefore possible to use a highly controlled, low-power laser (perhaps a semicon-

Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK. E-mail: jn@orc.soton.ac.uk

CREDIT: P. HUEY/SCIENCE

Published by AAAS

ductor diode) and boost its power with fiber amplifiers up to kilowatts.

The exquisite control offered by fiber at high power makes coherent beam combination an extremely exciting possibility for extending the power further, perhaps to the megawatt regime. There are a range of different methods through which the output beams of individual fiber sources can be combined (*8*, *9*), primarily to reach higher power and brightness than is possible from a single-fiber emitter. However, coherent combination in a phased-array laser configuration, rather like a radar antenna with active phase control of the individual beams, provides control of the spatial beam profile and a degree of beam steering and tracking (*10*). Digital holography is another version in which electronic means are used to control the beam profile (*11*). These are expensive systems, but costs can be reduced with simpler phase-control systems, provided that the laser phase noise is sufficiently low. Furthermore, although coherent beam combination has been restricted to continuous-wave systems, it is now being extended to the femtosecond pulsed regime (*12*).

Building on these results, the possibility of using coherently combined femtosecond fiber sources to drive wakefield accelerators for particle colliders is being explored (*13*). The multi-megawatt average power makes the efficiency levels that fibers offer a necessity. Although many thousands of fiber channels will have to be combined, the volume manufacturability, scalability, and reliability of active fiber technology makes this a tremendously exciting proposition for the next few decades.

References

1. R. J. Mears, L. Reekie, I. M. Jauncey, D. N. Payne, *Electron. Lett.* **23**, 1026 (1987).
2. Y. Jeong, J. K. Sahu, D. N. Payne, J. Nilsson, *Opt. Express* **12**, 6088 (2004).
3. E. Stiles, "New developments in IPG fiber laser technology," 5th International Workshop on Fiber Lasers, Dresden, Germany (2009).
4. R. D. Maurer, "Optical waveguide light source," U.S. Patent 3,808,549 (1974).
5. J. D. Kafka, "Laser diode pumped fiber laser with pump cavity," U.S. Patent 4,829,529 (1989).
6. E. Snitzer, H. Po, F. Hakimi, R. Tumminelli, B. C. McCollum, "Double-clad, offset core Nd fiber laser," in vol. 2 of *Optical Fiber Sensors*, OSA Technical Digest Series (Optical Society of America, Washington, DC, 1988), post-deadline paper PD5.
7. H. M. Pask *et al.*, *IEEE J. Sel. Top. Quantum Electron.* **1**, 2 (1995).
8. D. J. Richardson, J. Nilsson, W. A. Clarkson, *J. Opt. Soc. Am. B* **27**, B63 (2010).
9. T. Y. Fan, *IEEE J. Sel. Top. Quantum Electron.* **11**, 567 (2005).
10. T. M. Shay *et al.*, *Proc. SPIE* **7195**, 71951M (2009).
11. M. Paurisse *et al.*, *Opt. Express* **17**, 13000 (2009).
12. L. Daniault *et al.*, *Opt. Lett.* **36**, 621 (2011).
13. G. Mourou, D. Hulin, A. Galvanauskas, in *Super Strong Field in Plasmas*, D. Batani, M. Lontano, Eds. (American Institute of Physics, College Park, MD, 2006), pp. 152–163.

10.1126/science.1194863

PHYSICS

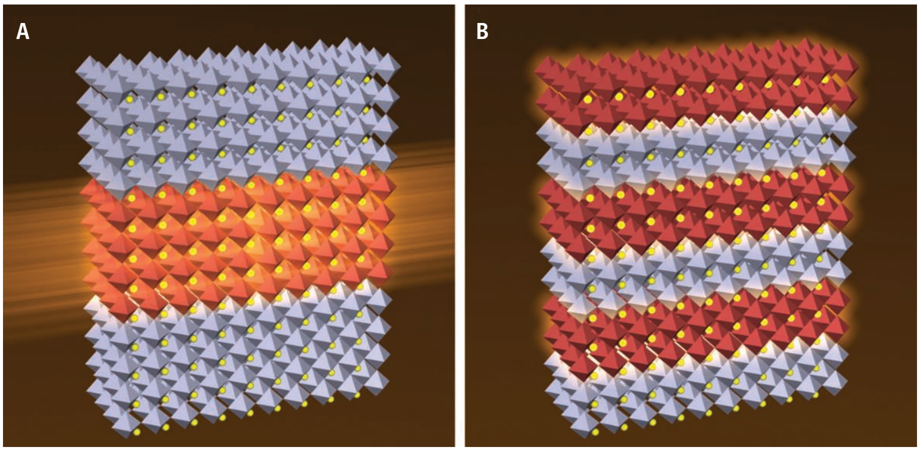
Shedding Light on Oxide Interfaces

The properties of a metallic oxide can be altered when it is confined as an ultrathin layer by layers of an insulating oxide.

German Hammerl[1] and Nicola Spaldin[2]

In the stable of solid-state materials, silicon is the workhorse. Its semiconductor properties are actually quite ordinary, but when other materials are harnessed to it to form interfaces, remarkable devices can be made that control the flow of electrical current with low applied voltages. In contrast, some transition metal oxides would be the stable's racehorses. Remarkable functional behaviors of this group include the ability to change from a metal to an insulator with a slight change in temperature, unusual magnetic properties, and even high-temperature superconductivity (*1*). Further novel properties are expected to emerge at interfaces created between transition metal oxides that already exhibit functional behavior, and these properties could be tuned through small changes in composition or by simply applying a bias voltage (*2*). However, like temperamental racehorses, the interfaces in these complex oxides can be more difficult to control than those formed by silicon. On page 937 of this issue, Boris *et al.* (*3*) report progress toward this goal by confining an ultrathin layer of lanthanum nickelate ($LaNiO_3$), normally a paramagnetic metal, between insulating lanthanum aluminate ($LaAlO_3$) layers, which leads to changes in its properties.

[1]Experimental Physics VI, Center for Electronic Correlations and Magnetism, University of Augsburg, Universitätsstr. 1, 86135 Augsburg, Germany. [2]Materials Theory, Department of Materials, ETH Zürich, Wolfgang-Pauli-Str. 27, 8093 Zürich, Switzerland. E-mail: german.hammerl@physik.uni-augsburg.de; nicola.spaldin@mat.ethz.ch



Thinner is different. Artistic illustration of two different electronic phases in heterostructures of $LaNiO_3$ (red), which is metallic as a bulk material, confined by $LaAlO_3$ (gray), which is a bulk insulator. (**A**) A confined $LaNiO_3$ layer that is four unit cells in thickness still shows metallic behavior. (**B**) When the thickness is reduced to two unit cells, a temperature-driven metal-insulator transition emerges.

The difference between semiconductors such as silicon and exotic transition metal oxides lies in the nature of the interactions between the constituent electrons. The electronic states of semiconductors are well described by conventional, single-particle band theory, in which individual electrons act independently. Contact between energy bands at interfaces can bend the bands or create energy barriers, which in turn can generate quasi-electric fields (which act on the charge carriers differently from true electric fields) or cause accumulation of charge carriers. In the complex oxides, however, there are strong correlations between the tightly

Published by AAAS