Large-mode-area designs enhance fiber laser performance.

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High Fiber

ILLUSTRATION BY RANDALL NELSON

Recent progress in fiber lasers has resulted in continuous wave (CW) powers as high as 810 W in a singlemode beam from a single-fiber system (see figure 1).[1,2] As work continues, it seems likely that researchers will generate 1.5 kW of output in a diffraction-limited beam (M^2=1) from a fiber laser before the end of the current year. We expect that single-emitter fiber lasers are capable of generating significantly higher output powers since the current results are largely limited by the available pump power.

The development of large mode area (LMA) fiber has played a key role in this rapid advancement. A typical LMA fiber features a 20-µm-diameter core with a 400-µm-diameter cladding (20/400 fiber); this compares to the roughly 10-µm-diameter core and 125-µm-diameter cladding for a conventional telecom fiber. The resulting increased mode-field diameter of LMA fiber reduces the detrimental effects of various nonlinear interactions such as stimulated Raman and Brillouin scattering, thus lifting the limits for achievable output powers (see ***oe**magazine*, January 2004, p. 32). Another key factor in the advance of fiber lasers is the increased power of commercially available diode laser stacks, as well as increases in their output beam brightness as a result of improvements in beam-shaping technology.

Optical-to-optical efficiencies of some of the rare-earth gain media used in fiber lasers are uniquely high; ytterbium, for example, provides up to 80% pump-to-signal light conversion, resulting in reported electrical-to-optical efficiencies of more than 40%.[3] As a result of improved power and beam quality, fiber lasers are achieving, and in certain aspects exceeding, the performance of incumbent high-power laser technologies such as neodymium-doped yttrium aluminum garnet, carbon dioxide, and thin-disk lasers.

Design Basics

At the heart of the fiber laser is the rare-earth-doped fiber, typically consisting of a double-clad (DC) fiber with an outer 400-µm-diameter (high numerical aperture (NA)) waveguide, and a ytterbium-doped, 20-µm-diameter (low-NA) central core waveguide. A high-power multimode pump beam launched down the

Some Diode Pump Configurations for Monolithic Fiber Lasers

Input Fibers to the Combiner (core/clad)	Output Fiber (diameter and NA)	Typical (max) Number of Input Fibers	Diode Pump Technology	Typical Power per Leg	Total Pump Power
105/125 0.22 NA	400 µm 0.46 NA	19 (37)	Pigtailed single emitter	3–5 W	95 W (180 W)
200/220 0.22NA	400 µm 0.46 NA	7 (7)	Fiber-coupled diode bars	10–25 W	70–175 W
400/440 0.22NA	400 µm 0.46 NA	3 (3)	Fiber-coupled bars and stacks	30–200 W	90–600 W

outer waveguide is absorbed by the doped inner core, creating the required population inversion and, hence, gain. Lasing occurs along the inner waveguide, which largely defines the laser transverse modal structure and the resulting beam quality. Optimum fiber lengths are typically 10 to 40 m, depending on the pump wavelength, doping level, and the overlap between the doped core region and the outer pump waveguide. A large-diameter outer waveguide offers advantages for easier coupling of the required high pump power but ultimately necessitates a longer fiber length.

Fiber lasers consist of three main parts: a fiber-coupled array of diode pumps fusion-spliced to an active fiber, a DC fiber with an active rare-earth-doped core, and a pair of in-core fiber Bragg gratings that operate as cavity mirrors, providing selected-bandwidth feedback at the desired wavelength. Such monolithic designs are well established for standard singlemode-core DC fibers; they should become equally ubiquitous for LMA DC fiber lasers in the future.

Multiple suppliers produce the high-power and high-brightness diode stacks suitable for a kilowatt fiber laser with $M^2 \sim 1$, making it feasible to commercialize such a system. The relatively high cost of state-of-the-art pump technology makes it unlikely that widespread commercialization of kilowatt-class singlemode fiber lasers will occur in the near term, however, at least not until the price becomes competitive with that of other established laser technologies. Nevertheless, for applications such as defense, the practical advantages of the technology can outweigh cost issues.

It's in the Fiber

Recent advances in LMA fibers have led to the increase in fiber-laser pulse energies and peak powers. Several groups have generated pulses with durations of about 100 ns and energies of several millijoules in a single transverse mode.[4] Others have achieved multimode beams with energies of up to 30 mJ.[5] Results even include nanosecond pulses with peak powers in the range of hundreds of kilowatts, with the highest reported peak power for sub-nanosecond pulses reaching to about 1 to 2 MW.[6]

Several groups have obtained these results using two different pulsed-laser configurations. Q-switched fiber lasers offer the advantage of fewer parts in the laser cavity but produce relatively long pulses at fixed repetition rates. Diode-seeded, pulsed fiber amplifiers offer the flexibility of adjustable pulse shapes, durations, and repetition rates, but require more amplification stages to reach high energies. Developers have yet to demonstrate these high pulse energies and peak powers at average powers greater than 100 W. Achieving average powers commensurate with those of the CW counterparts of fiber lasers requires further development of advanced LMA fiber designs that support single-transverse mode operation with larger mode areas or, alternatively, with significantly reduced nonlinearities.

Fiber aside, the development of all-integrated LMA-DC CW fiber technology is far from complete. Critical components, such as fused-fiber pump combiners for diode-pumped LMA fiber and Bragg gratings in the LMA cores are still in the early stages of development. Technological challenges, such as splicing of LMA fibers, have hindered the rapid advance as well. Splicer technology was largely developed for telecom fiber, with its 125-µm cladding, and is not necessarily compatible with larger cladding diameters; also, since in an LMA fiber core more than one mode can be excited, mode-matching requirements for two LMA fibers at the splice point are particularly stringent.

From a commercial standpoint, it is very important that some standardization of rare-earth-doped (usually ytterbium) LMA fiber designs begin to take place. Such standards are critical to help the technology mature from its roots in research to a widely adopted laser technology suitable for high-volume manufacturing. In recent months, multiple suppliers have released 20/400 LMA fiber designs featuring low-NA cores (typically around 0.06) and claddings with NAs in excess of 0.46. Evidence for this standardization comes not only from the supply of the doped fiber in this particular geometry, but also the increasing availability of compatible components such as pump combiners for use with 20/400 output fiber and gratings.

Standardization of the doped fiber designs will enable component manufacturers to develop the required platform of these support components (pump couplers, fiber Bragg gratings, isolators, etc.) needed to make the desired

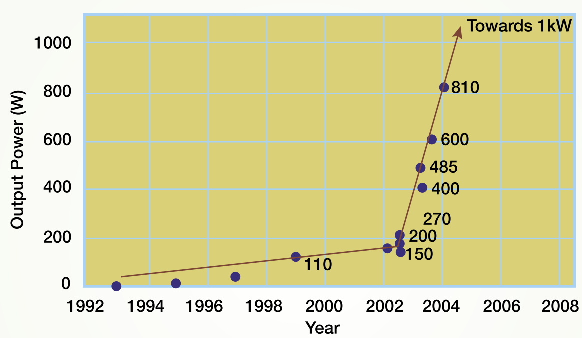

Figure 1 Advances in fiber design and pump sources have resulted in dramatic improvements in CW fiber laser power scaling.

all-fiber LMA cavities. This process will in turn encourage splicer manufacturers and test and measurement companies to extend product lines to accommodate these non-telecom fiber geometries. Collectively, this should significantly reduce the cost of fiber laser technology, thus making its practical advantages more accessible.

One major practical advantage of fiber lasers is the stable and robust architecture of the all-fiber cavities formed using fiber Bragg gratings for the high reflector and output couplers. Fiber Bragg grating fabrication is compatible with high-volume, low-cost manufacturing methods such as those already adopted for the erbium-doped fiber amplifiers used in telecom. The success of LMA fiber designs for active gain fiber has forced the development of compatible (mode-matched) photosensitive fibers and optimization of the fiber Bragg grating manufacturing process. Fiber optimization includes the glass composition as well as critical control of the key optical and geometrical tolerances to operate at the required high powers. Progress in these components is continuing and the recent demonstration of linearly polarized LMA fiber lasers capable of generating better than 300 W of CW output shows the applicability of this grating technology to high-power laser operation.

Pump Combiners and Diode Pumps

The majority of the results shown in figure 1 have been achieved through free-space pumping with high-power diode laser bars. Practical implementation of monolithic designs, however, requires fused-fiber pump combiners, which will most likely integrate a larger number of lower-power diode-laser pump sources. Several compelling technological advantages of low-power diode lasers support this strategy: high reliability, more efficient heat management, and simple cost-effectiveness.

Recent advances in the manufacturing process of high-power fused-fiber pump combiner technology allow developers to combine three, seven, 19, or more, individual pump lasers. These improvements allow the devices to accommodate significantly higher powers than their standard telecom counterparts (see figure 2).[7] Again, standardization of the gain-fiber geometries will help coupler manufacturers reduce the number of custom options, thus lowering cost.

A range of options exists for pumping a typical 20/400 LMA fiber laser, ranging from the combined output of 19 individual 5-W emitters (95 W total) to the combination of three 200-W high-powered, beam-shaped diode stacks (see table). Alternatives include direct end pumping using an 800-µm, 0.22-NA fiber-coupled diode laser source, a bi-directional pump architecture, and the adoption of wavelength-multiplexed diode bars. The broad absorption band of ytterbium-doped glass allows ytterbium-doped fiber to be pumped by diode lasers operating at 915, 940, and 976 nm, a factor that further expands the range of options available, and, more importantly, the list of potential pump laser suppliers. Such flexibility allows selection of sources based on the cooling requirements, diode lifetime, package size, and electrical requirements of a particular application. Of equal importance, the cost of the diode pump source can be well matched to the available budget.

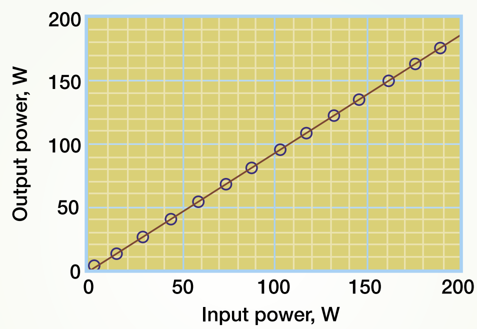

Figure 2 Improvements in coupler technology allow coupler geometries such as the 1 × 3 fused-fiber pump combiner to carry significant amounts of optical power.[8]

Future Development

Most of the advances in high-power fiber lasers have been achieved in ytterbium-doped fiber lasers operating in the 1060- to 1110-nm wavelength region, which features efficiencies around 75%. Other rare-earth-doped fiber lasers, such as eye-safe erbium: ytterbium (Er:Yb) co-doped lasers (1550 nm) or thulium lasers (2 µm), operate with efficiencies significantly higher than those of their bulk-laser counterparts. Both types of systems are potentially attractive for military and commercial lidar applications, either directly or as high-brightness pump sources for bulk solid-state lasers. Power scaling results in these fibers have advanced over the last two years, with a 50-W Er:Yb system under development for free-space communications and 100-W systems available.[8] The medical laser field provides another area of opportunity for such compact, efficient fiber laser sources.

Despite current achievements, it is unlikely that fiber lasers have reached the limits of their technological potential. We expect further significant increases in output powers, perhaps approaching 10 kW of CW output from a single fiber. Although standard LMA fibers are commercially available, researchers are working on novel advanced fiber designs, including LMA photonic-crystal fibers and hollow-core amplifying photonic-crystal fibers with low nonlinearities. It is too early to be sure whether these or other novel approaches will provide practical solutions, but the need for new fiber designs is ever present, defined by the demands of developing practical fully-monolithic fiber lasers and by the challenges of further power scaling. **oe**

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