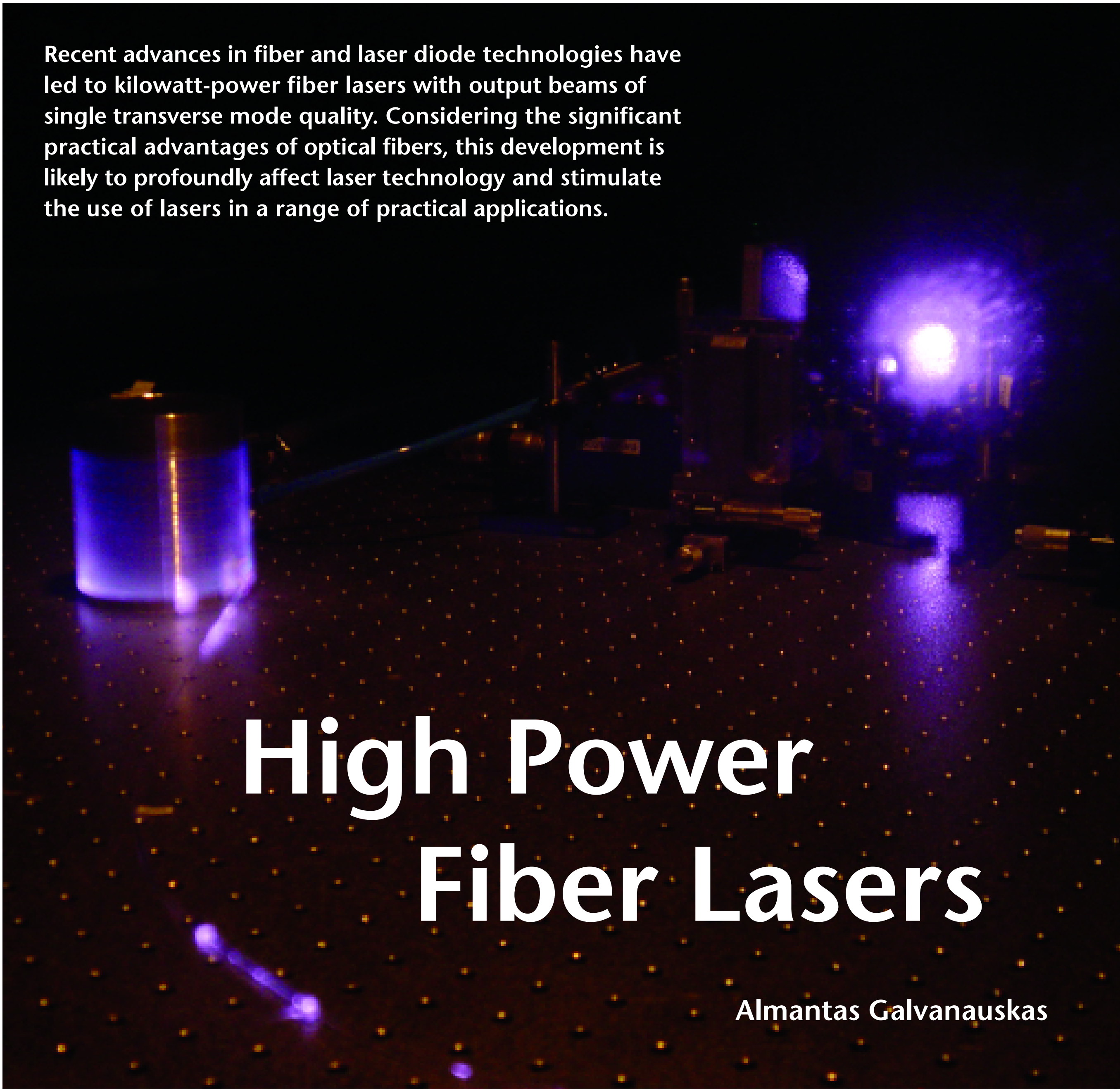

Recent advances in fiber and laser diode technologies have led to kilowatt-power fiber lasers with output beams of single transverse mode quality. Considering the significant practical advantages of optical fibers, this development is likely to profoundly affect laser technology and stimulate the use of lasers in a range of practical applications.

High Power Fiber Lasers

Almantas Galvanauskas

A technological revolution is occurring in the field of solid-state lasers: there has been a rapid, large increase in the power produced by fiber laser systems. Over the past two years, the level of power that can be produced in a diffraction-limited beam has increased from ~100 watts to nearly 1 kilowatt.[1-3] This breakthrough has been driven primarily by two factors: the emergence of large mode area (LMA) fibers and progress in the development of high brightness semiconductor diode pumps. LMA fibers have contributed to the achievement of higher laser powers in three ways: by reducing the detrimental effects of nonlinear interactions in the fiber core; by reducing the susceptibility of fibers to optical damage; and by allowing for use of larger cladding sizes—and, thus, larger usable pump powers—in double-clad fibers.

Fiber lasers are the most powerful solid-state laser technology available today: they are capable of providing diffraction-limited power nearly two orders of magnitude larger than those that can be produced by use of conventional solid-state lasers. The rise of fiber lasers is even more significant in view of how practical they are to use. Their technological platforms—monolithic, compact and at the same time highly efficient—can be produced in a way that is very different from the complex and highly skilled assembly processes typically required for the production of conventional open-cavity lasers. The assembly process required for a fiber laser platform is, in fact, more akin to the way in which electronic equipment is built.

Compact, reliable, efficient, cost-effective fiber lasers could potentially replace most of today's conventional solid-state lasers in a shift that could

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significantly advance the majority of laser applications. The combination of high power and ease of use could benefit applications in a wide variety of fields, including semiconductor device manufacturing, surgery, military technology, industrial material processing, remote sensing and imaging and scientific instrumentation.

The fiber power revolution

The remarkably rapid rise in continuous wave (cw) fiber laser output powers that has been reported by several research groups over the past few years is illustrated in Fig. 1. This figure shows only the results achieved in a single transverse mode. Indeed, fiber lasers with multimode outputs have produced even higher cw powers: an array of combined fiber lasers with an output power close to 10 kW has been reported.[4] Along with the growth in average powers, the emergence of LMA technology has made possible a number of equally remarkable achievements in the areas of peak powers and pulse energies. As illustrated in Fig. 2, millijoule pulse energies and peak powers higher than 1 MW have been demonstrated with single transverse mode and multimode outputs.[5-8]

Since the increase in power has been achieved essentially by use of off-the-shelf Yb-doped double-clad (DC) fibers, it may well lead to the commercial availability of kilowatt-power cw lasers in the very near future. Figure 3, for example, shows the characteristics of cw fiber lasers with output power of up to 810 W, a level achieved by use of commercially available 20-μm core Yb DC-LMA fiber.[3] A measured single transverse mode profile which corresponds to $M^2 = 1.27$ is shown in the inset to Fig. 3. It is expected that more advanced designs of LMA fibers will enable achievement of even higher powers—perhaps in the range of > 1 kW to ~10 kW—with a single fiber emitter.

The technological breakthroughs of today were preceded by a long history of research and development. The first rare-earth-doped fiber lasers were demonstrated in the early 1960s,[9, 10] but after these pioneering efforts by Elias Snitzer, work in fiber lasers essentially came to a halt because of the lack of suitable pump

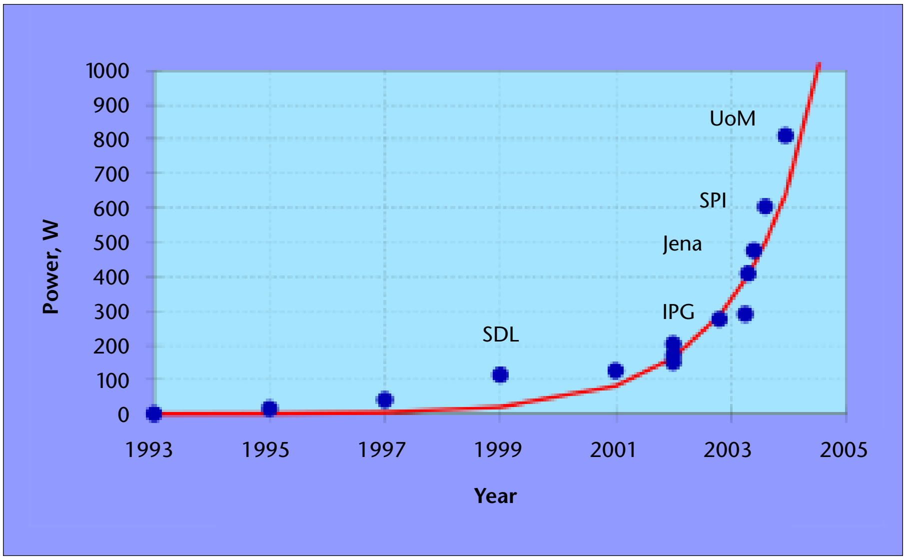

Figure 1. Power achieved with CW fiber lasers (near diffraction-limited beam quality).

sources. The first fiber lasers were, in fact, lamp pumped! It took more than 20 years for diode pumps to reach maturity.

With the emergence of optical communications, the first practical erbium-doped fibers suitable for single-mode diode pumping were demonstrated in 1986 in the 1550-nm communications fiber low-loss window.[11] When fiber lasers received this "second start" in optical communications, high efficiency and robust, compact packaging of rare-earth-doped fiber were seen as the main advantages of use as a gain medium. With average powers that ranged from a few milliwatts to at most tens of milliwatts, the technology was not considered capable of achieving the same power levels as conventional solid-state lasers. The first fiber lasers and amplifiers—unlike those demonstrated in the early 1960s—were single-mode devices in which both pump and signal propagated in a small-diameter fiber core which supported only a single transverse mode. Single-mode pumping requires single-mode diodes, which are both expensive and intrinsically limited as far as achievable power is concerned.

The next significant step forward in the evolution of fiber laser power was the introduction of cladding pumping.[12] In 1988, a group led by Snitzer demonstrated successful operation of a double-clad fiber structure in which a low-brightness pump from a broad stripe multimode diode was coupled into an inner cladding which surrounded a single-mode fiber core. If the geometry and size of the cladding are appropriate, the propagating pump can be efficiently absorbed in a single-mode core doped with active ions so as to produce optical gain for a single-mode signal propagating in the core. In essence, this fiber configuration converts a low brightness pump beam into a diffraction-limited signal beam at the fiber laser or amplifier output.

The development of this technique led to a gradual increase in fiber laser powers in the intervening decade: a laser emitting 35 watts of power was reported in 1998; 110 watts were reported in 1999. The primary driving force was the continuing advancement of diode laser pump technologies, which led to increasing diode powers and brightness, at a decreasing cost per watt. A significant step in the enabling fiber technology was the introduction of Yb-doped silica fibers, which could provide high absorption—thus facilitating high power pump coupling—at unprecedented levels of optical efficiency.

The most recent step in the trend toward higher power has been the introduction of LMA-DC fibers.

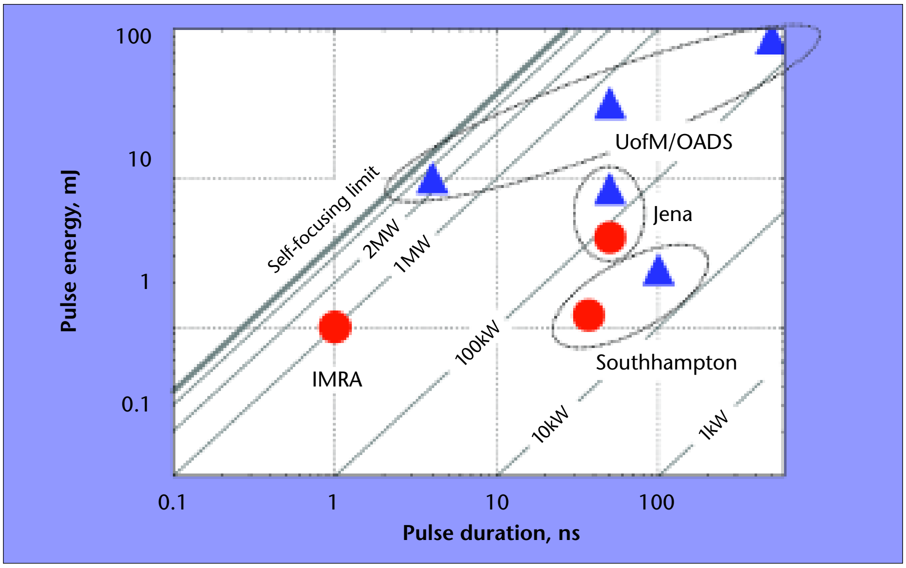

Figure 2. Pulse energies and peak powers achieved with LMA fibers as reported by different groups between 2000 and 2004. Red circles represent results achieved with single transverse mode output beams; blue triangles represent results achieved with multimode output beams. Note that for multimode ns-pulsed beams, energies of up to 27 mJ and peak powers of up to 2.4 MW (and for single mode up to 4 mJ and 1 MW) have been reported.

Large mode area fibers

The development of optical fibers has traditionally been driven primarily by the need to minimize temporal pulse spreading in long range optical communication links. Starting in the 1970s, the trend was to move from large multimode to small single-mode fiber cores; in the single-mode core, intermodal dispersion is absent, and temporal broadening of propagating pulses is much smaller compared to multimode fibers.

Today, however, the need to achieve high average and peak powers in fiber lasers is pushing the development of double-clad optical fibers in the opposite direction: fiber core (and cladding) sizes are gradually increasing, even beyond strictly single-mode core dimensions, while preserving nearly single-transverse mode output quality. In Fig. 4, a standard telecommunication single-mode fiber (SMF-28) and a typical LMA-DC fiber are shown for comparison. Typical high power LMA-DC fiber dwarfs telecommunication fiber in both core diameter (30 μm versus 10 μm) and cladding size (400 μm versus 125 μm).

Since the magnitude of laser-signal distortions induced by nonlinear effects is inversely proportional to fiber mode area, the LMA-DC fiber shown in Fig. 4, with a mode area more than 10 times larger than that of a standard fiber, has correspondingly lower susceptibility to nonlinear distortions compared to a standard core. In a DC fiber, a large core also improves the core-to-cladding area ratio and enhances pump absorption, allowing use of shorter fibers. Since the magnitude of the nonlinear distortions is also proportional to the distance a signal propagates in a fiber, shorter fibers are less susceptible to nonlinearity. What's more, a large pump cladding size facilitates pump coupling, thus effectively increasing available pump power.

The advantage of LMA fiber over standard single-mode fiber in reducing nonlinear distortions can be fully appreciated with the help of a simple numerical example. Stimulated Raman scattering (SRS) typically sets power-handling limits in cw and long-pulse fiber lasers and amplifiers. SRS threshold power for the fundamental fiber mode is $P_{cr} = 16\, A_{mode}/\, L_{eff} \cdot g_R$, where g_R is the Raman gain coefficient in a fiber glass, A_{mode} is the mode area and L_{eff} is the effective signal propagation length in a fiber amplifier. In describing signal propagation in an amplifying fiber, effective propagation length $L_{eff} \approx 1/g$ replaces the true propagation distance L because the pulse peak power P increases along the fiber $P(z) = P(0)\exp(gz)$ (assuming constant gain along the fiber). Here, g is the amplifier gain coefficient related to the total amplifier gain G (in dB) and amplifier length L through $g = G/4.34L$. For the Yb-doped LMA fiber with 30 μm and 0.06 NA core shown in Fig. 4, mode field diameter (MFD) is ~ 24 μm at $\lambda = 1.064$ μm and $A_{mode} = 452\ \mu m^2$. Standard single-mode fiber at the same wavelength typically supports a fundamental mode with ~ 6.2-μm MFD and corresponding $A_{mode} = 30\ \mu m^2$.

Assuming a typical cw fiber amplifier length of 30 m and total gain of 30 dB, the SRS threshold for the LMA fiber amplifier is $P_{cr} = 314$ kW, while for a standard fiber amplifier it would be only $P_{cr} = 21$ kW. For cw fiber lasers, the SRS threshold calculation is more complicated than for amplifiers and corresponds to much lower threshold values. Nevertheless, the ratio of threshold powers between LMA and standard fibers is substantially maintained, with the SRS threshold for SM cw fiber lasers typically in the 100-W range and that of LMA in the kilowatt range.

But the maximum core supporting a single transverse mode is significantly constrained by physical limitations. Step index fiber is single mode when its normalized frequency parameter V, which is defined by the core radius R_{core} and core-to-cladding refractive index difference through $V = R_{core} \cdot (2\pi/\lambda) \sqrt{(n^2_{core} - n^2_{cladding})}$, fulfills the requirement $V \leq 2.405$. For this reason, increasing the core size with a fixed core-to-cladding refractive index difference eventually leads to a multimode core with more than one transverse mode being guided. The refractive index difference must be correspondingly reduced to keep the core single mode at large core diameters. Unfortunately, however, this leads to weak guiding in the core, which makes the fiber mode unacceptably sensitive to bending loss and in practice renders such low NA fibers useless. This limits

SM core size at λ = 1.064 μm to a diameter of approximately 10 μm.

Because LMA fibers with core sizes larger than 10 μm support more than one transverse mode, it is necessary to employ specific techniques to achieve single-mode operation of LMA fiber based lasers and amplifiers. The emergence of these techniques has been the main factor leading to the most recent phase of the evolution in fiber laser power. They are based on the notion that for high quality LMA fibers, the intermodal scattering coefficient d_{mode}, which describes power transfer between the two closest modes per unit propagation length, can be kept relatively small so as to support propagation that is nearly single mode over relatively short fiber lengths. Intermodal power scattering is caused by imperfections in the fiber, such as microbending deformations or fiber flaws.

Fiber flaws can be minimized by taking special care during the fiber draw and preform fabrication process; microbending deformations, on the other hand, are determined by fiber geometry.[13] In practice, by use of relatively short lengths of high quality LMA fiber, it has proved possible to achieve a nearly diffraction-limited beam for single (fundamental) mode excitation.[14] After the mode is excited, however, if there is no mechanism to suppress the effect of scattering, at high powers the mode is susceptible to mechanical and thermal perturbations occurring in the fiber laser or amplifier itself.

To make an LMA fiber laser or amplifier resistant to such perturbations, in the most widely used approach, higher order modes in a coiled low-numerical-aperture fiber are filtered to offset the effect of intermodal scattering.[15] The underlying principle is that higher order modes are less confined than fundamental modes; when the fiber is bent with a certain radius of curvature, higher order modes can thus experience much larger loss compared to the fundamental mode. In qualitative terms, the principle can be explained by the optical tunneling effect (see Fig. 5). The straight fiber refractive index profile is represented by a step function in a transverse dimension (a), the peak of which corresponds to high refractive index of the core. Effective refractive indices and profiles of the guided modes for the fundamental and the next higher order mode are shown here.

The guided modes can be said to be trapped in the core by the total internal reflection (TIR) from the low refractive index barrier formed by the cladding. Fiber curvature can be represented by an induced constant slope of the refractive index profile in the transverse dimension, as shown in Fig. 5 (b) [see Ref. 16]. The slope effectively narrows the refractive index barrier on one side of the core; at a specific radius of curvature, the barrier will become narrow enough to frustrate TIR for a mode, which will then "escape" into the cladding. Since the effective refractive indices of higher order modes are lower that that of the fundamental mode (the fundamental mode is the "slowest" mode), there is a curvature radius range at which the higher order modes "jump" the barrier and the fundamental mode remains in the core. Figure 6 shows an example of calculated modal losses for a 30-μm and 0.06-NA step-index core LMA fiber as a function of curvature radius.

The difference in confinement—or, in other words, the difference in effective index values—between the fundamental mode and higher order modes falls with increased core size. For the technique to be used, the maximum core size is thus

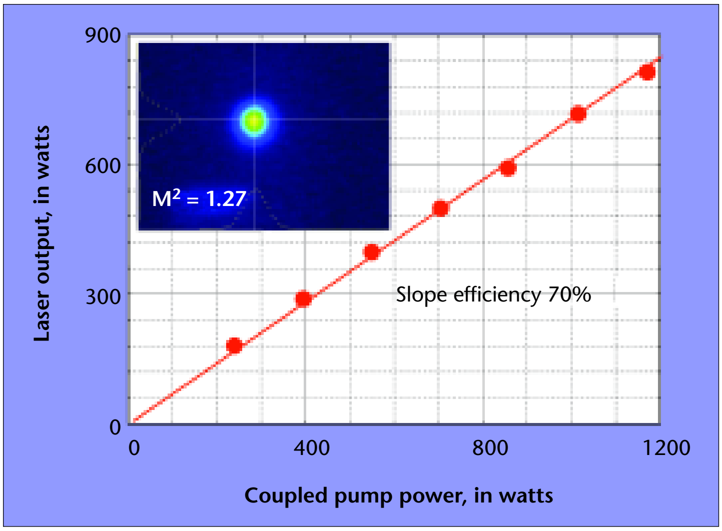

Figure 3. Measured power characteristics and beam quality of 810-W fiber laser built using 20-μm core Yb-doped double-clad fiber.

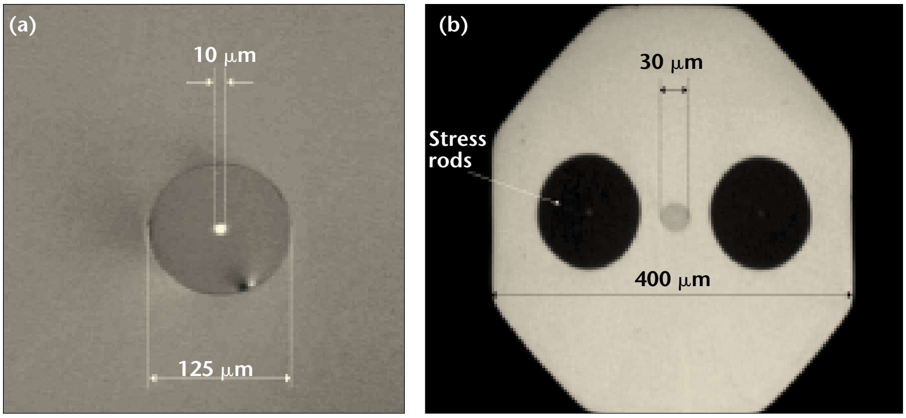

Figure 4. Size comparison between standard telecommunication and double-clad LMA fibers. (a) Single-mode fiber with 10-μm core and 125-μm cladding (SMF-28), (b) LMA fiber with 30-μm core and 400-μm cladding. Note two large stress rods surrounding the core, which are designed to produce strong birefringence in the core.

limited in practice to approximately 30 µm, with a 20-µm core being the most typical size. A drawback of the coiling technique is that it requires a low NA core. This makes it difficult to achieve the high Yb-doping concentrations necessary for the implementation of short fiber lasers and amplifiers (Yb is an index-increasing dopant). It also complicates the fabrication process and makes it difficult to use the coiling technique with Er/Yb co-doped DC fibers, where it is very difficult to achieve low NA.

An alternative based on single-mode photonic crystal fibers (PCF) has recently emerged. In this type of core, modal guiding is achieved by a completely different mechanism than in an index guiding core. Photonic crystal guiding appears to somewhat reduce bending losses for low-numerical-aperture large-core fibers. There have been reports[17] of single-mode PC fibers with ~30-µm MFD and a bending radius that is, in practice, acceptable. But further increases in mode size (mode sizes of ~ 40 µm have been reported recently) lead to prohibitively high bending loss; this makes it necessary, in turn, to keep such single-mode LMA-PC fibers straight, which renders them unsuitable for use in packaged laser systems.

Fiber laser pumping

As mentioned earlier, the second key factor in the upsurge in fiber laser power has been the increase in the power and brightness of semiconductor diode pumps. It is important to note, however, that advances in diode technology have been matched by progress in the design of double-clad fibers. As discussed above, large core fibers made possible an increase in the size of the fiber cladding and, as a consequence, in usable pump power. Equally important to the process has been the development of large NA claddings.

Since light guiding in a DC fiber cladding is achieved through TIR, the usefulness of a particular source for pumping a DC fiber is determined by its beam quality (BQ) factor. $BQ = M^2 = \theta_{diverg.} \cdot w_{waist} \cdot \pi n/\lambda$, where $\theta_{diverg.}$ is the divergence of a beam focused into a spot with radius w_{waist} in the medium with refractive index n. Only if $\theta_{diverg.} \cdot w_{waist} \leq \theta_{cladding} \cdot R_{cladding}$, where $NA_{cladding} = \sin(\theta_{cladding})$ and $R_{cladding}$ is the fiber cladding radius, can all of the pump power, in principle, be coupled into the cladding of a DC fiber. This explains the continuing search for new polymer cladding materials with high NA that are suitable for coating double-clad fibers. The broad availability of new fluoroacrylate coatings with higher numerical aperture has led to the recent shift from $NA_{cladding} = 0.35$ to $NA_{cladding} = 0.47$ in the majority of commercial DC fibers.

As an alternative, a completely new approach to cladding design has been inspired by the fiber fabrication techniques recently developed for microstructured and photonic crystal fibers. The air-clad design relies on what is, in effect, an air-glass interface at the cladding outer surface to achieve a large $NA_{cladding}$. Large numerical apertures—measuring more than 0.7—have been demonstrated for such DC structures.

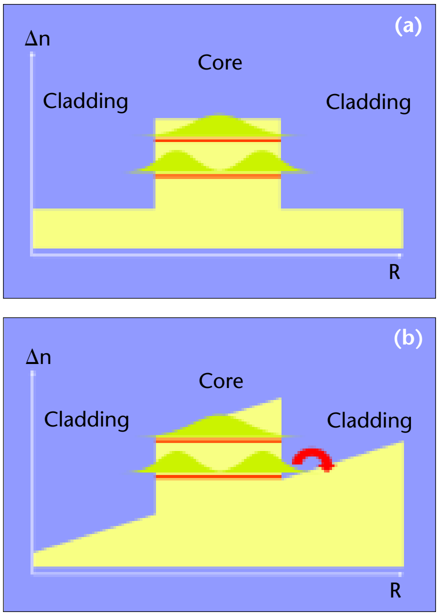

Figure 5. Higher order mode filtering in a coiled fiber through an optical tunneling effect. (a) Uncoiled fiber: all modes are trapped in the core by the high-index step. (b) Fiber curvature induces refractive-index slope, lowering the barrier on one side and allowing modes to escape from the core into the cladding.

Thermal robustness and optical efficiency

Fiber geometry itself is a major contributor to high power generation. A fiber is essentially a very long, thin cylinder with a large surface-to-volume ratio which offers very efficient dissipation of pump-deposited heat. This dissipation is orders of magnitude better than that of a conventional bulk solid-state gain medium—except, of course, in the case of thin-disk lasers which also have large surface-to-volume ratios. This is illustrated in Fig. 7, which shows the calculated temperature distribution along a 1-kW pumped 30-m long DC Yb-doped fiber laser. The configuration of the fiber laser that appears in Fig. 7 is the same as that shown in Fig. 3, which was used to generate 810 W of cw output. It is remarkable that in the case of a fiber that has been cooled simply by immersion in water, the increase in temperature is only several degrees centigrade. Clearly, such superb thermal properties are suitable for sustaining average powers that are much higher than the 1 kW achieved so far.

An important aspect of this high power scaling is the uniquely high efficiency of some of the rare-earth dopants. It is no accident that all the recent high power results have been achieved with Yb-doped fibers, which offer optical-to-optical efficiencies as high as 80 percent. This also leads to much lower fiber heating, since only a small fraction of pump power (less than 20 percent) is transferred through thermal relaxation processes to the fiber glass host.

Monolithic lasers

Although most of the power scaling results shown in Fig. 1 were achieved by means of laboratory type fiber laser setups with free-space pump light coupling, fiber lasers can be built as monolithic systems, with optical pump and signal beams completely in-fiber. Several diode fiber-pigtailed pumps can be coupled into a DC fiber cladding by use of a monolithic pump and signal combiners. This combiner consists of several relatively large diameter pump-fiber leads fused together with a signal-carrying fiber, which contains a core matching that of a LMA-DC fiber. Fused pump fibers are typically: tapered at the end to match the dimensions of DC fiber cladding; cleaved; and then spliced to a rare-earth-doped active LMA-DC fiber. As far as the market is concerned, 6 + 1 (six pumps + one signal) and even 19 + 1 pump and signal combiners are becoming commercially available for use with 20-μm core LMA-DC fibers. Since such couplers are monolithic, they can sustain high average powers (up to 200 W has been reported so far[18]). Although the maximum power coupled through such a combiner into a DC fiber is typically smaller than that achieved by use of free-space end-coupling, in the very near future further development of high-brightness diodes should lead to monolithic LMA fiber lasers with kilowatt output. An important practical aspect of use of such diode-combining schemes is that several low power diodes can be used instead of a single high power one, which makes possible the use of long lifetime diodes. Indeed, 50-W diode lasers with lifetime greater than 40,000 hours are becoming available commercially, which enables construction of highly reliable, monolithic high power fiber lasers.

Future outlook

As high power fiber lasers evolve, researchers are seeking to achieve greater power levels, higher pulse energies and, perhaps most importantly, devices that are completely monolithic. It is likely that within the next few years, research and development efforts will continue to extend output powers with a single transverse mode output into the several kilowatt range. Since current approaches to producing LMA fibers are close to their limits in terms of the mode size that can be achieved, the development of new, larger mode fiber designs and single-mode operation techniques would be highly advantageous. One new idea is to reduce the nonlinearity of DC fibers by using hollow-core rare-earth doped PCF.[19] At this point, however, it is unclear whether this and other emerging techniques will ultimately lead to practical solutions.

Fiber geometry naturally offers another promising avenue of power scaling. Indeed, since several fibers can easily be packaged together, optical combination of the outputs of these fibers could lead to much higher powers than individual fibers can provide on their own. A variety of techniques for the coherent and incoherent combination of fiber lasers is now being studied and developed. This means that ever more spectacular advances will be made in the future.

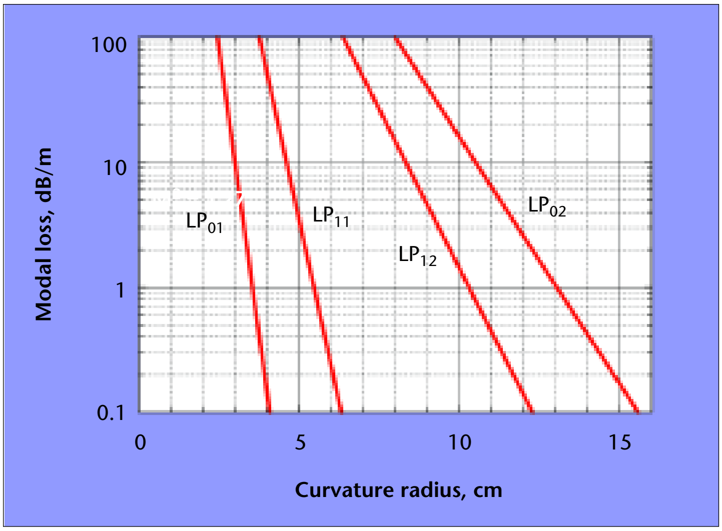

Figure 6. Calculated example of modal losses as a function of curvature radius for different modes in 30-μm diameter and low NA (NA = 0.06) fiber core.

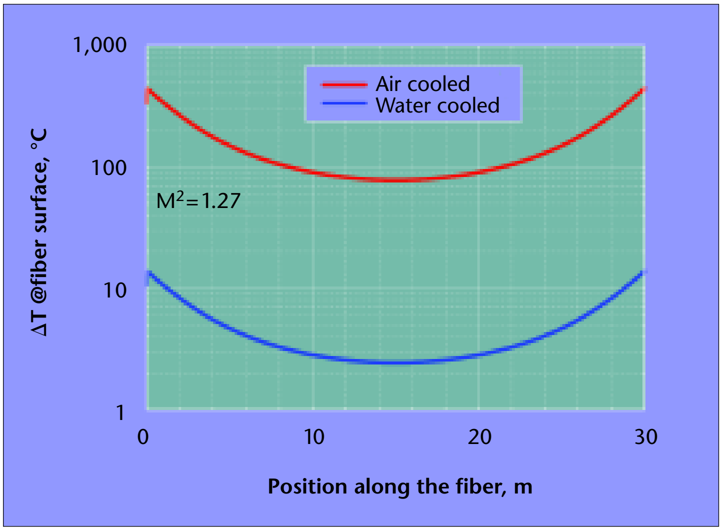

Figure 7. Calculated temperature-rise distribution at the fiber surface along a 1-kW pumped 30-m long fiber laser for the cases of heat exchange through convection in air (red curve) and heat conduction in water (blue curve).

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