Fiber based high power laser systems

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Abstract: The first rare-earth-doped fiber lasers were operated in the early sixties, and produced a few milliwatts at a wavelength around one micron [1, 2]. For the next several decades, fiber lasers were little more than a low-power laboratory curiosity. Recently, however, fiber lasers are entering the realm of kilowatt continuous-wave powers with diffraction-limited beam quality, delivering 100 W average power and millijoule pulses in the short pulse regime. In this article we review the reasons for this power evolution.

Introduction

The pursuit of highest power together with highest brightness is most efficiently fulfilled by diode-pumped rare-earth-doped solid-state lasers. The most common solid-state laser geometry is a rod, with dimensions of few millimeters in diameter and several centimeters in length. However, conventional rod lasers suffer from thermo-optical problems, which restrict simple power scaling by maintaining a good beam quality. Several geometries of the gain media have been developed to overcome this limitation, such as the thin disk [3] or slab [4] geometries, which reduce thermo-optical distortions due to their special geometry.

A promising alternative to bulk solid-state laser systems are rare-earth-doped fibers, whose properties, achievements and potential in several operation regimes will be reviewed in the following section.

Rare-earth-doped Fiber Lasers

Alternatively to forming the gain medium as a thin disk, making the gain medium long and thin also leads to outstanding thermo-optical properties. This fact is due to the large ratio of surface-to-active volume of such a fiber, resulting in excellent heat dissipation, and the distribution of the thermal load of a considerable long length. This constitutes the concept of a rare-earth-doped fiber laser. As a result, thermal distortion of the beam is negligible, and the beam quality depends primarily on physical design of the fiber.

Figure 1 shows a fiber laser in its simplest form. In general, both the pump and laser radiation is guided in an active doped waveguide structure. The laser cavity can be constructed by dielectric mirrors or fiber Bragg gratings on the fiber ends. This complete integration of the laser process leads to the inherent compactness and long-term stability of fiber lasers, because no components are necessary in a long free-space cavity.

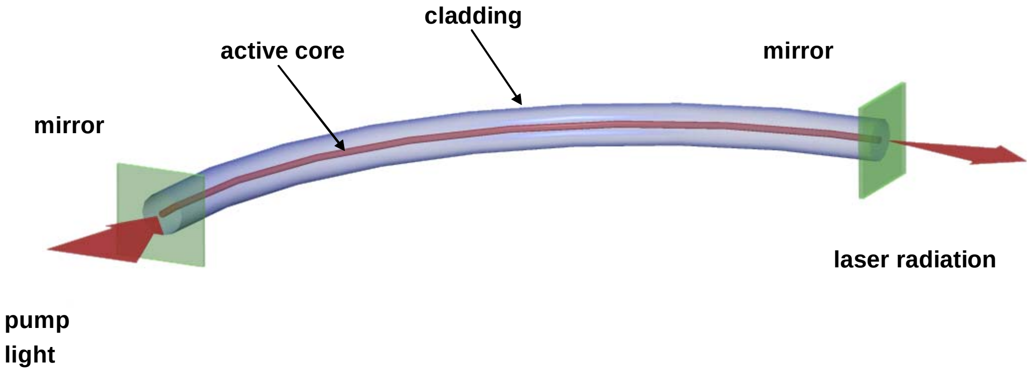

Fig. 1: Schematic illustration of a fiber laser.

However, to pump conventional single-clad fibers, where just the rare-earth-doped single-mode core can guide light, spatially coherent pump sources are required. Single-mode pump diodes are limited in power to a few watts. This limitation can be overcome by the use of the double-clad fiber design. Here, the active doped core is surrounded by a second waveguide, which is highly multimode, shown in Figure 2. In this second waveguide, also called inner cladding or pump core, low brightness high power diode lasers can be launched. This pump light is gradually absorbed over the entire fiber length and is converted into high brightness high power laser radiation. Thus, the double-clad concept can be used as a highly efficient brightness improvement using the laser process in rare-earth ions.

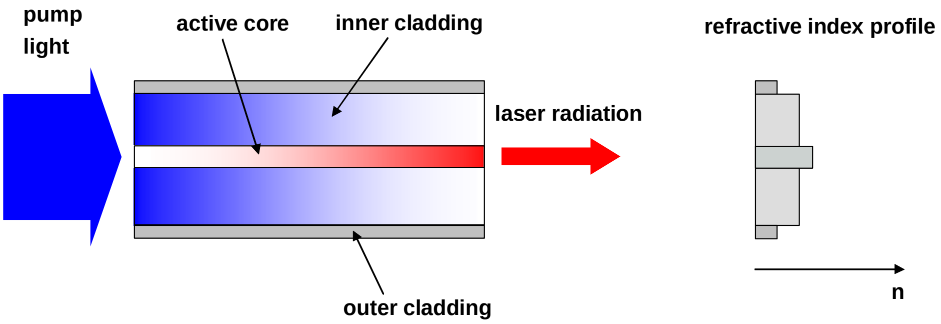

Fig. 2: The double-clad fiber concept.

Due to the confinement of both the laser and pump radiation, the intensity is maintained over the entire fiber length and is not limited by diffraction to the Rayleigh length as it is the case in longitudinally pump bulk lasers. The gain of the laser medium is determined by the product of pump light intensity in the gain medium and interaction length of the input laser radiation with that medium, e.g. the absorption length. This decisive product can be orders of magnitude higher in fibers than in other bulk solid-state lasers, consequently rare-earth-doped fibers possess a very high single-pass gain. This leads to a very efficient operation of fiber laser systems, with very high gain and low pump threshold values. Especially ytterbium-doped glass fibers, which have a quantum defect of less than 10%, can provide optical-to-optical efficiencies well above 80%. This is why ytterbium is the first choice among all rare-earth-ions if high power average levels are aimed.

The drawback of the double-clad fiber concept is the reduced pump light absorption. Intensity distributions can exist in the inner cladding, which have no overlap with the doped core leading to a degradation of efficiency. The pump light absorption can be significantly improved by breaking the cylindrical symmetry of the inner cladding. Geometries, such as D-shaped or rectangular pump cores, prevent the propagation of such undesired intensity distributions of the pump radiation by permanently mode mixing. Alternatively, the absorption of pump radiation can be enhanced in symmetrical fibers using the technique of periodic bending of the fiber, i.e. a kidney shaped fiber, as shown in Figure 3.

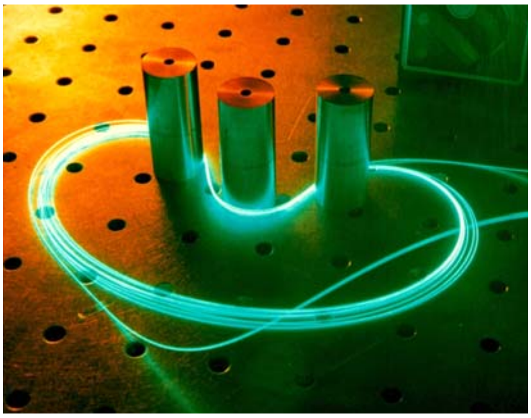

Fig. 3: Improvement of pump light absorption due to periodic bending.

Owing to the mentioned outstanding thermo-optical properties of a rare-earth-doped fiber high power continuous-wave generation can be considered as a straightforward problem. Several single-mode double-clad fiber lasers producing output powers in excess of 100 W have been reported already three to five years ago when the race of increasing power of fiber lasers has started [5,6].

As opposed to conventional diode-pumped solid-state laser systems the significantly longer interaction length and the tight confinement of the laser radiation enforces disturbing nonlinear effects [7], which constitute the main restriction of rare-earth-doped fiber based laser systems. Since SiO_2 is a symmetric molecule, contributions of the second-order susceptibility vanish for silica glass fibers. Thus, the lowest-order nonlinear effect in optical fibers originates from the third-order susceptibility, consequently, an optical field propagating through a fiber experiences nonlinear effects such as self-phase modulation (SPM), stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). Nonlinearity basically limits the performance of rare-earth-doped fiber systems before limitations due to thermo-optical effects or fracture of the fiber are reached. This is the dominant challenge if high peak powers from pulsed fiber based laser system are generated, but counts even for the generation of continuous-wave radiation. The above-mentioned results of single-mode ytterbium-doped fiber lasers in the 100 W class are mainly limited by the onset of stimulated Raman scattering.

However, using innovative fiber designs such as large-mode-area fibers, a significant reduction in power density in the fiber core can be achieved with the retention of the outstanding thermo-optical properties. Most applications require diffraction-limited beam quality. The lowest refractive index step of a doped core which can be reliably fabricated with conventional MCVD fiber perform manufacturing technique is $\sim 1*10^{-3}$. The requirement of single-transverse mode confinement translates this into a maximum core diameter of ~15 µm in a conventional, step-index fiber in the one-micron wavelength region. A larger core would normally lead to the propagation of higher-order transverse modes. However, several techniques have been demonstrated to ensure single-mode operation in slightly multimode fibers, such as the application of bend losses [8], which are significantly higher for higher-order transverse modes compared to the LP_{01} mode. Therefore, a properly coiled fiber can prefer single-mode operation in a fiber that would otherwise be slightly multimode [9]. Other approaches depend on a preferential gain to the fundamental mode [10,11], tapered sections along the fiber [12] or careful excitation of the fundamental mode at the beginning of the multi-mode fiber [13]. By applying these techniques, experimentalists have extracted diffraction-limited output from a step-index, multimode fiber with a mode-field-diameter as large as 30 µm [14].

The efficiency of the approach of low-numerical aperture large-mode-area fibers we have demonstrated in a high power continuous-wave fiber laser already in end of 2002 [15]. At an overall launched pump power of 700 W we reached an output power of 485 W without any degradation and a nearly diffraction-limited beam quality out of a 25 µm core.

Since this demonstration of the potential of power scaling of fiber lasers and amplifiers with diffraction-limited beam quality using low-numerical aperture large-mode-area fibers, numerous high power single-transverse mode fiber lasers have been realized by several research groups. Pioneering contributions are done at the University of Southampton, the University of Michigan, the University of Tokyo, IPG Photonics and the group of the authors of this article. Their main achievements are summarized in the chart shown in Figure 4, illustrating an enormous power increase in the two last year. This evolution, which can be considered as a renaissance 40 years after the invention of a fiber laser, has its origin in the discussed inherent properties of rare-earth-doped fibers, but also in the progress of fiber manufacturing technology and availability of reliable high power diode laser pump sources. Today, up to ~ 2 kW of continuous-wave power with single-mode beam quality has been demonstrated [16,17], which is certainly not the end of the pursuit.

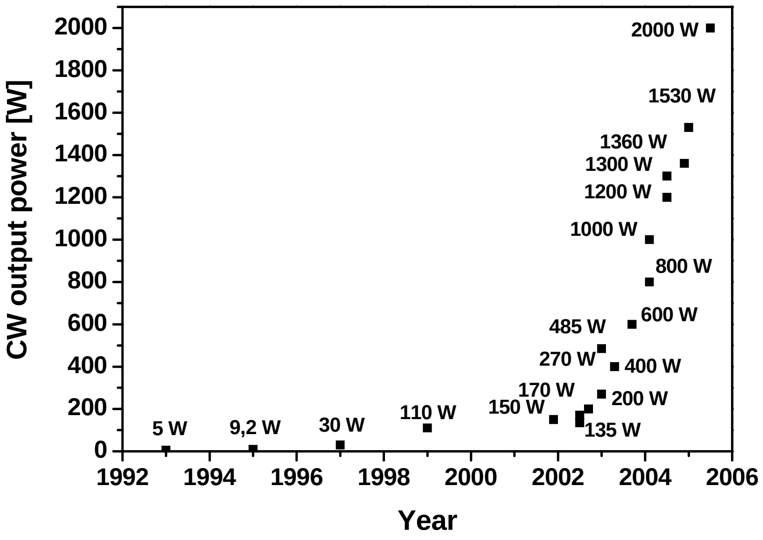

Fig. 4: Power evolution of cw double-clad fiber lasers with diffraction-limited beam quality over the last decade

Recently, a new class of fibers, so called photonic crystal fibers (PCF), had emerged. Microstructuring the fiber adds several attractive properties to conventional fibers, and that is why PCFs, or “holey fibers,” are currently subject of intense research [18]. Their main advantages arise from the enormous design flexibility and high precision. PCFs have several interesting and novel features, including the capability of being strictly single-mode over a large wavelength range [19], a property referred as “endlessly single-mode”. The inverse interpretation of this property means, that the mode area of a PCF theoretically can be scaled to infinity at a given wavelength. Of course, this is limited by increased propagation losses with increased core diameter.

The cladding of PCFs consists of a triangular array of air holes. Intuitively, one can imagine that the “average” refractive index of the cladding is decreased by the air holes, so that light is guided in the core by modified total internal reflection. The refractive index step can be controlled in the range of ~$1*10^{-4}$, an order of magnitude lower than in conventional step-index fibers. Consequently, intrinsically single-mode ytterbium-doped cores with diameters up to 50 µm have been demonstrated [20]. Figure 5 shows an example of such a microstructured low-nonlinearity fiber, the mode-field diameter is as large as 45 µm.

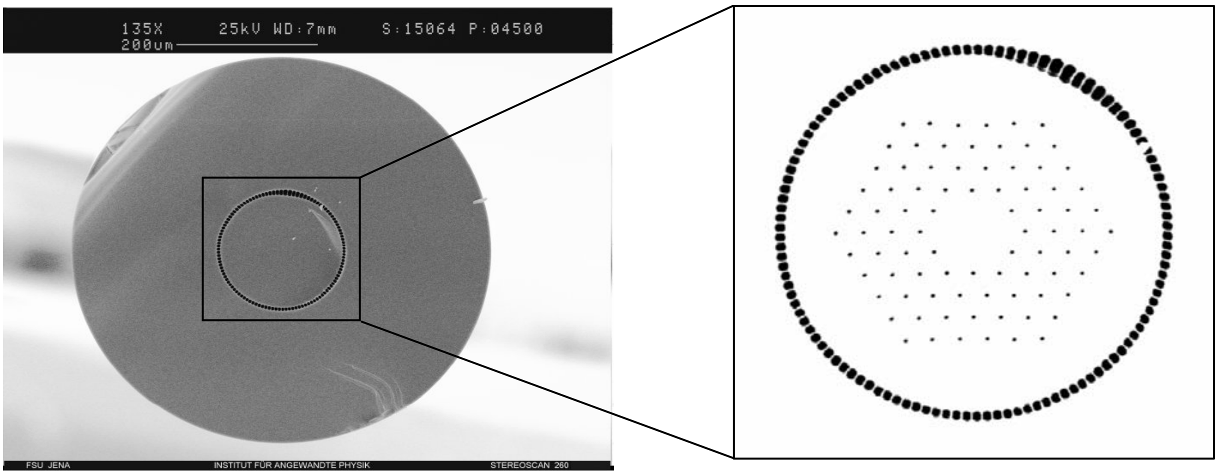

Fig. 5: Cross section of a low-nonlinearity single-mode air-clad photonic crystal fiber

A further advantage of microstructuring a fiber is the possibility of forming an air-cladding region to create double-clad fibers, also shown in Figure 5. Double-clad PCFs can be achieved by surrounding the inner cladding with a web of silica bridges which are substantially narrower than the wavelength of the guided radiation. The result is a significantly greater index difference between the inner and surrounding region, a therefore a higher numerical aperture, than can be achieved by conventional polymer coated fibers [21,22].

Indeed, we believe that PCF lasers due to their unique have the potential to revolutionize rare-earth-doped fiber lasers in high-power operation. The first step in this direction has recently been done with a 1.53 kW emission out of an ytterbium-doped photonic crystal fiber [23]. The output characteristic of the high power fiber laser with nearly diffraction-limited beam quality is shown in Figure 6.

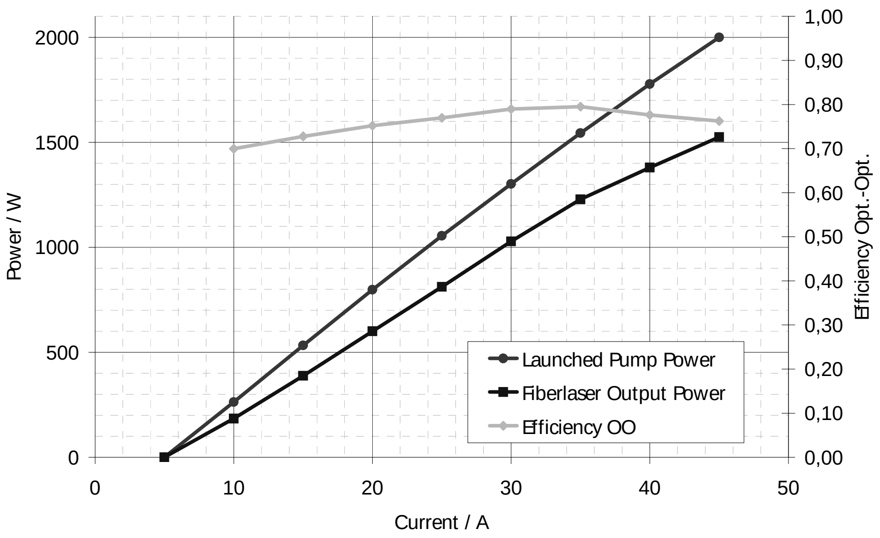

Fig. 6: Output characteristic of the 1.53 kW photonic crystal fiber laser.

Here the question arise which power levels are possible from a single fiber laser. Limitations due to fiber damage, thermal loading and nonlinear optics have to be taken into account to answer this. The following analysis bases on a single-mode core with a mode-field diameter of 35 µm. The results are summarized in Figure 7.

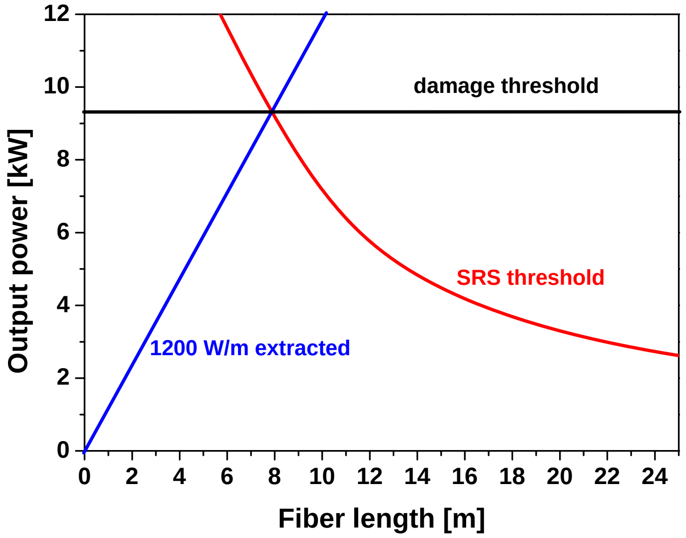

Fig. 7: Summary of thermal, damage and nonlinearity limits of a continuous-wave fiber laser with a 35-µm MFD core.

The surface damage of fused silica is approximately 2 GW/cm^2, although this value is significantly reduced in doped glasses. Damage thresholds greater than 1 GW/cm^2 for doped glass has been demonstrated experimentally, and this value leads to a damage threshold of about 9.2 kW in a core with a mode-field diameter of 35 µm (black line). Figure 7 reveals, to extract this power level of nearly 10 kW the fiber has to be shorter than ~8 m to avoid the onset of stimulated Raman scattering (red line). Consequently, the extracted power per unit length is ~ 1200 W/m. The resulting thermal load, which is in the case of Yb-doped fibers approximately 10% of the extracted power, can not be handled by conventional air-cooled fiber anymore. However, e.g. water cooling provides improved heat dissipation by two orders of magnitudes and is easily implemented. This analysis reveals that a power level of ~ 10 kW with diffraction-limited beam quality is possible applied established fiber technology. Thus, today's power levels of continuous-wave fiber lasers are not fiber limited, rather than by available pump power.

Pulsed Fiber Lasers

In the pulsed regime, nonlinear processes play a more dominant role and restrict power and energy scaling. However, rare-earth-doped fiber offer features which make them even look promising in this challenging operation regime. The high single-pass gain allows for simple amplification schemes, instead of multi-pass or regenerative amplification, and the average power scalability makes fiber based short-pulse laser systems interesting for applications which ask for high energies in combination with high repetition rates.

Of course, even more advanced fiber designs are necessary the overcome the mentioned restrictions. One example is the rod-type photonic crystal fiber [24]. The basic idea of this fiber design is to have outer dimensions of a rod laser, meaning a diameter in the range of a few millimeters and a length of just a few tens of centimeters, but including two important waveguide structures, one for pump radiation and one for laser radiation. A cross section of such a fiber together with an experimental setup is shown in Figure 8. Finally, such a fiber has an extremely reduced nonlinearity and therefore allows for significant power and energy scaling. In continuous-wave operation power levels well above 100 W are demonstrated. In the q-switched regime the significantly reduced cavity length allows for much shorter pulses than obtained in conventional fiber lasers. Such a short-length ytterbium-doped rod-type photonic crystal fiber produced pulse durations well below 10 ns [25]. At repetition rates up to 100 kHz pulse energies up to 0.5 mJ and average powers in excess of 30 W have been obtained in single-transverse mode beam quality. These results are just pump power limited, the fiber design offers scalability to significantly higher performance, which makes this laser source interesting for several applications ranging from machining, range finding to XUV radiation generation.

(a) (b)

Fig. 8: (a) Microscope image of a rod-type photonic crystal fiber and (b) experimental setup of the rod-type fiber laser.

There are basically two approaches to generate high power femtosecond pulses in rare-earth-doped fibers. One is to use nonlinearity, the other is to avoid nonlinearity. In the first, the combined interaction of normal dispersion, gain and nonlinearity (self-phase modulation) can create linearly chirped parabolic pulses, which resist optical wave breaking [26]. The linear chirp can be removed using a grating compressor resulting in high power femtosecond pulses. Pursuing this approach of direct amplification of femtosecond pulses in fibers followed by a fiber power amplifier 40 W average power of 150-fs pulses has been demonstrated [27]. Second way leads to a rare-earth-doped fiber based chirped-pulse amplification (CPA) system employing the above mentioned low-nonlinearity large-mode-area fibers. Figure 9 shows the experimental setup of the ytterbium-fiber CPA generating up to 131 W of 220 fs pulses at 73 MHz repetition rate [28]. To our knowledge this is the highest average power ever reported for ultrashort-pulse solid-state laser systems and, more important, the result is just pump power limited.

In order to increase to pulse energy in these systems, we introduce a pulse picker setup. The reduced pulse repetition rate, typically between 10 kHz and 1 MHz, leads to pulse energies up to several 100 µJ (approaching the mJ level) at several 10 W average power. The obtained results in our labs together with the recent developments in fiber technology make us confident that 100 W average power millijoule pulse energy sub-picosecond fiber laser systems will be possible very soon. This performance, in particular the significantly higher repetition rate compared to conventional femtosecond lasers, allows for unique approaches in several application fields, e.g. high speed and high precision micromachining of metals and pumping of nonlinear optical processes such as parametric amplifiers.

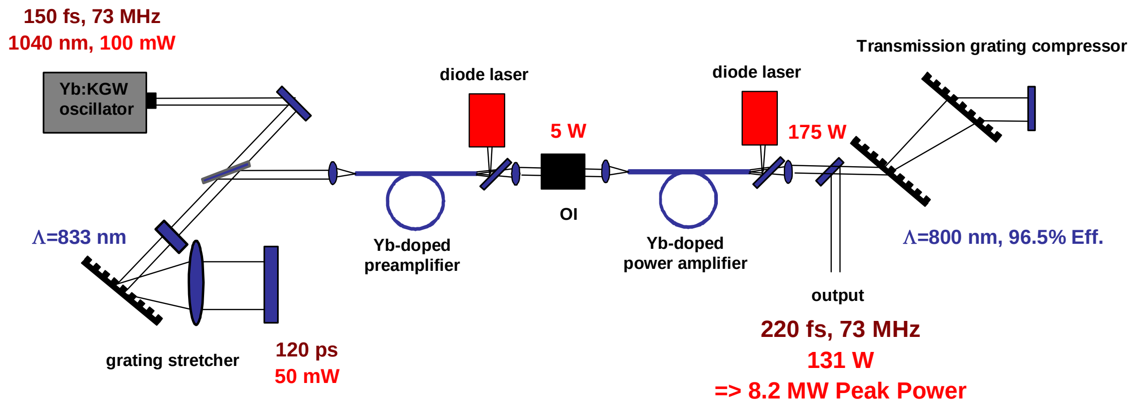

Fig. 9: Schematic setup of the high average power fiber CPA system.

Conclusions

As discussed, with the advent of reliable, high-brightness, diode pump lasers – and of double-clad fibers to facilitate coupling the pump light into the fiber – fiber lasers are entering kilowatt power range with diffraction-limited beam quality. Compared to bulk solid-state lasers, the chief advantage of fiber lasers is their outstanding heat-dissipation capability, which is due to the large ratio of surface to volume of such a long, thin gain medium. Fiber lasers and amplifiers have a very high single-pass gain and therefore low laser thresholds and can be efficiently pumped with diode lasers. Moreover, the broad gain bandwidth, the compactness, robustness and simplicity of operation make fiber lasers attractive for a host of applications. Rare-earth-doped PCFs offer several unique properties, which allow an upward scaling of the performance compared to conventional fiber lasers. Their main advantages are the very high pump core NA and an extended possible mode area of truly single-mode cores. More generally, these latest investigations of transferring more functionality to the fiber by microstructuring indicate that such systems have an enormous potential to scale the performance of next generation laser systems.

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