High-power ytterbium-doped multicore fibers☆

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A B S T R A C T

Fiber lasers are nowadays one of the preferred coherent light sources when high average powers up to the multi-kW regime are targeted. Additionally, they are also widely employed for the generation of ultrashort pulses with moderate energy in the mJ-range. However, numerous physical limitations currently hinder a further performance scaling. One way to overcome these limitations is the coherent beam combination of parallel amplifiers. This approach has led to laser systems operating beyond the limits of a single amplifier, albeit at the cost of an increase in footprint and complexity. Amplifying multicore fibers hold the promise to combine the simplicity of fiber lasers with unprecedented performance scaling prospects and the additional benefit of enabling dynamic beam and pulse shaping. In this paper, basic considerations about design parameters of multicore fibers with non-coupling cores are given and the impact of physical effects on the output emission is discussed. State-of-the art results of multicore-fiber-based laser systems are reviewed with these fibers now being able to output kW-level average powers and nanosecond pulses with over 100 mJ pulse energies. Finally, an outlook regarding future performance targets and possible applications is given.

1. Introduction

Fiber laser systems have undergone an unprecedented growth in performance since their first experimental demonstration. In fact, just a few decades after the first double-clad amplifying fiber was presented [1,2], optical fibers are nowadays able to amplify light up to average powers in the multi-kW regime [3]. This extraordinary performance increase was possible thanks to the remarkable properties of optical fibers. First of all, the fiber geometry (with a large ratio of length to diameter) results in a high radial heat flow that allows for simple cooling concepts, e.g. with flowing water. It should be mentioned that this characteristic is not exclusive of optical fiber and similar considerations also apply to other advanced solid-state laser concepts such as the thin-disk laser or slab-laser to enable high average-power output [4,5]. In addition to the geometry, the material most optical fibers are made of, i. e. fused-silica, offer an unique combination of acceptable heat-conductivity, low absorption for radiation in the near-infrared spectral region [6] and good mechanical stability. This fiber host material brings

additional advantages since silica fiber fabrication processes have reached maturity and techniques such as stack-and-draw [7] or deep-hole drilling [8] have made possible the realization of many of the advanced designs presented in this paper. Moreover, some of these fibers can be spliced to other optical components (such as beam-splitters and isolators) creating robust, alignment-free systems, something that is quite unique amongst solid-state laser systems. Another crucial advantage when using optical fibers to amplify light is that their waveguide nature (both for the signal and the pump light) allows for long interaction lengths between the light and the active medium, which leads to very high single-pass, optical-to-optical efficiencies [9]. In fact, the ability to capture and guide low brightness pump light (enabled by the introduction of the double-clad design) allows benefiting from the rapid progress in power and efficiency of semiconductor pump diodes. Finally, the fiber has predefined input and output points for the beams and these do not change significantly with the output power, which eases alignment and reduces maintenance effort.

Thanks to all the advantages mentioned above, fiber amplifiers are

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arguably the most prominent laser technology today when it comes to reaching the highest averages powers in the CW regime with nearly diffraction-limited beam quality. In fact, multi-kW systems are commercially available from multiple vendors. However, an effect discovered around 2010 known as transverse mode instability (TMI) [10], has brought the once exponential average-power growth [11] to an almost complete halt over the recent decade. This thermally induced effect causes a temporally unstable energy transfer from the fundamental mode to higher-order modes, i.e. causing a fluctuation of the output beam profile pattern when the average-power reaches a certain average power threshold. TMI has been observed in almost every known fiber design and while certain passive and active mitigation strategies have been successfully applied [12–19], a complete solution has not been found yet.

On the negative side, the fiber geometry (that is so beneficial to achieve high average powers) promotes the onset of nonlinear effects due to the long interaction length of the high intensity light guided in the (usually) small fiber core with the silica glass [20]. In this context, in pulsed systems, non-linear effects have a more severe impact than TMI. The reason is that, while average power scaling issues can limit the repetition rate, non-linear effects limit the pulse-energy and peak-power, which can completely render fiber amplifiers unfit for certain applications. For example, the maximum possible peak-power in a fiber is 4 MW (for linearly polarized light), limited by catastrophic damage caused by the self-focusing effect [21]. Besides, there are a number of less severe non-linear effects, such as self-phase-modulation (SPM), that progressively degrade the temporal and spectral characteristics of the pulses [22]. In addition, in high-energy operation material damage can occur especially at the fiber surface interface [23]. All of these issues can be mitigated by reducing the intensity of the light in the fiber. This can be achieved by either increasing the waveguide diameter, or by increasing the pulse duration with techniques such as chirped-pulse-amplification (CPA) [24]. The first approach can be achieved without sacrificing beam quality with the use of advanced fiber designs [7,20,25–29]. However, even the best state-of-the-art designs are still limited in size at a certain point [30]. In addition, the operation of these ultra-large core fibers with high average power operation leads to a shrinking of the mode size [31] which counteracts this effort. The second approach, which can be used in combination with the first one, is the application of CPA. Even though this is heavily employed in laser systems, it is also limited by spectral bandwidth requirements and by the size of the components required for stretching and compression [32]. State-of-the-art, femtosecond, fiber CPA systems combine these two approaches, which allows them to reach pulse energies in the mJ-range with peak powers of GWs [33]. And yet, in spite of this, the maximum achievable energy/peak power often falls short compared to other laser architectures for pulse durations in the nanosecond range and shorter.

Hence, a paradigm shift is required to make fiber amplifiers a viable technology for applications requiring high pulse energies and high average powers. Similar to other research fields, such as high-performance computing or telecommunication [34], the parallelization of laser amplification [35–38] has been identified as a way forward. Due to some of the advantages already described above, such as the low complexity of single-pass fiber amplifier setups and the well-defined output beam position and shape, this concept has been successfully applied to fiber lasers. Parallel amplification combined with coherent beam combination [39,40], allows for the simultaneous scaling of the average power and the pulse-energy/peak-power, while preserving (and sometimes even enhancing) the beam and pulse quality of a single amplifier. As a result, this concept has already demonstrated record performance values with 10 kW average power [41] for ultrashort pulses, and pulse energies surpassing 10 mJ [42]. Furthermore, this concept is not limited to Ytterbium-doped fibers, and it has also been applied, in the same basic configuration, to Thulium-doped fibers [43]. In addition to the raw power scaling, the use of an array of individual beams also enables shaping of the output beam (in the far field) [44,45]

just by manipulating the relative phases of the individual beams, which opens up the possibility of dynamic beam control.

However, using multiple single-core amplifiers for this task results in an increase of complexity with a growing number of amplification channels. This, in general, comes with a corresponding increase in footprint requirements and cost. In this respect, multicore fibers (MCFs) offer a way to integrate these different amplification channels back into a single fiber, thus restoring the simplicity fiber laser systems without compromising performance. The structure of the paper is as follows: In section 2, basic considerations about design parameters of multicore fibers with non-coupling cores are given and the impact of physical effects on the output emission is discussed. This is followed by section 3 where recent state-of-the-art results of laser systems based on MCFs are presented, both for average power and pulse energy scaling. Section 4 describes the use of multicore fibers for beam and pulse shaping, i.e. going beyond pure power scaling. Finally, in the last section, an outlook is given regarding future developments also in combination with applications that can be targeted with MCF laser systems.

2. Multicore fibers – Basic considerations

MCFs are routinely used in a wide span of fields ranging from telecommunications [46–48] to sensors [49] and microscopy [50], just to mention a few. Additionally, they seem well suited to be used as a parallelized amplifier system, something that was recognized early on [51].

The basic concept of an MCF offers many degrees of freedom when looking at possible design parameters, with an exemplary structure shown in Fig. 1. The signal cores can have different structures (e.g. step index), may have different sizes and can be arranged in different patterns. Additionally, for amplifying MCFs, the mechanism of pump light coupling and guiding also has to be carefully considered.

In a first classification of amplifying MCFs, they can be segregated into fibers where the signal cores are optically independent and the ones where they are coupled. The latter configuration mostly targets guiding one super-mode, which intensity is spread across multiple cores [52–54]. However, for high power/high energy operation this is not an attractive concept since the power is not equally distributed across the different cores. Thus, considering the performance-limiting effects in fiber laser systems, this leads to a degradation of the power scaling potential of these structures. Hence, this paper focuses on MCFs where the signal cores are optically independent, as this maximizes the scaling potential of MCFs for high power operation.

2.1. Optical decoupling of cores

Physically speaking the cores of a MCF within a shared pump cladding are always optically coupled [55]. This is because, theoretically, speaking the evanescent field of a core mode extends over the whole fiber cross-section and, therefore, it will always have an overlap with neighboring cores. This is what, ultimately, leads to core-to-core coupling in multicore fibers [56]. However, for the practical point of view what really matters is the length over which the coupling (i.e. a significant power transfer between cores) happens. Crucially, this coupling length can be influenced with proper design measures in such a way that only a negligible amount of energy is transferred between cores over the device length. In this case it is considered to be an MCF with optically decoupled cores. There are several possible approaches to achieve this. The first, and simplest one, is to make the pitch between neighboring cores large enough so that the evanescent electric field of the light propagating in one core has a negligible overlap with neighboring cores. This can be quantified by defining a threshold to the acceptable amount of power that can be transferred between cores. This cross-talk reduces the coherent beam combination efficiency and causes additional problems in the presence of nonlinear effects, e.g. it introduces pulse distortions [57,58]. Besides, increasing the pitch-to-core
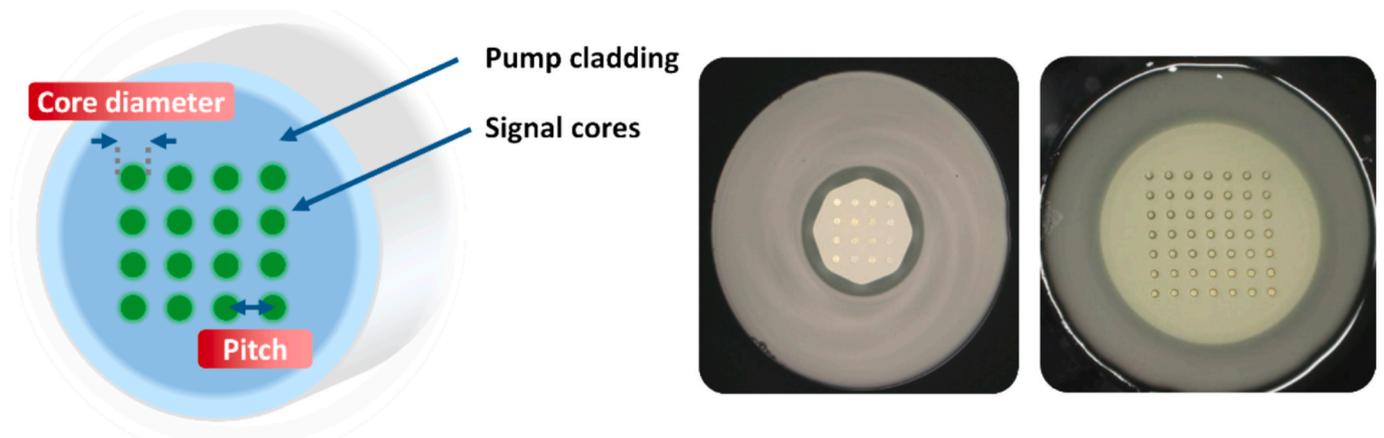
Fig. 1. Left: Schematic structure of a multicore fiber with multiple single cores doped with a laser active material distributed across a shared pump-cladding. The core diameter and pitch are important parameters that influence core-to-core coupling. Right: Microscope images of the end-facets of Ytterbium-doped rod-type multicore fibers with 4x4 and 7x7 cores.

ratio can lead to a reduction of pump absorption (i.e. fill factor of the cores in the cladding), which can be problematic in some systems (especially those limited by non-linearities as longer fibers might be required). Additionally, the optical coupling can be, in general, reduced by introducing optical barriers between said cores [59], but a detailed discussion about this general approach falls outside of the scope of this paper. However, an easy, soft implementation of the optical barrier concept is to increase the refractive index step of the cores. Additionally, these two measures can be combined, which opens up a wide design space that has been recently numerically explored in search for optimized designs [55].

As an example, the minimum index-step required to limit core-to-core coupling to 1 % in a 1 m long MCF is shown in Fig. 2 as a function of the relative pitch and the core diameter [55]. As can be seen, for smaller core sizes and cores that are closer together, the required index step has to be increased, which might lead to the loss of single-mode operation in the cores. In fact, looking at the V-parameter [60] isolines in Fig. 2, it can be seen that there are configurations (e.g. all with relative pitch values < 2.5 and V-parameter > 2.405) that require intrinsic multimode/few-mode cores to limit core-to-core coupling to 1 %. However, this limit can be relaxed based on experimental experience, since a value of $V < 3.0$ still allows for fundamental mode excitation and operation in the cores. Thus, a pitch-to-core ratio between 2.5 and 3.0 gives a good compromise between a high fill factor (and, potentially, pump absorption) and low optical coupling.

A way to avoid optical coupling even with closely packed cores is the introduction of optical barriers between them. This concept is widely used in telecommunication where very long transmission lengths in the kilometer range are required [61,62]. Even though there have also been some first tentative implementations for high average power MCFs [63], they are not widely spread yet.

2.2. Polarization of the output beams

Another point that is of great importance for applications is the output polarization pattern of the beams emitted by the MCF.
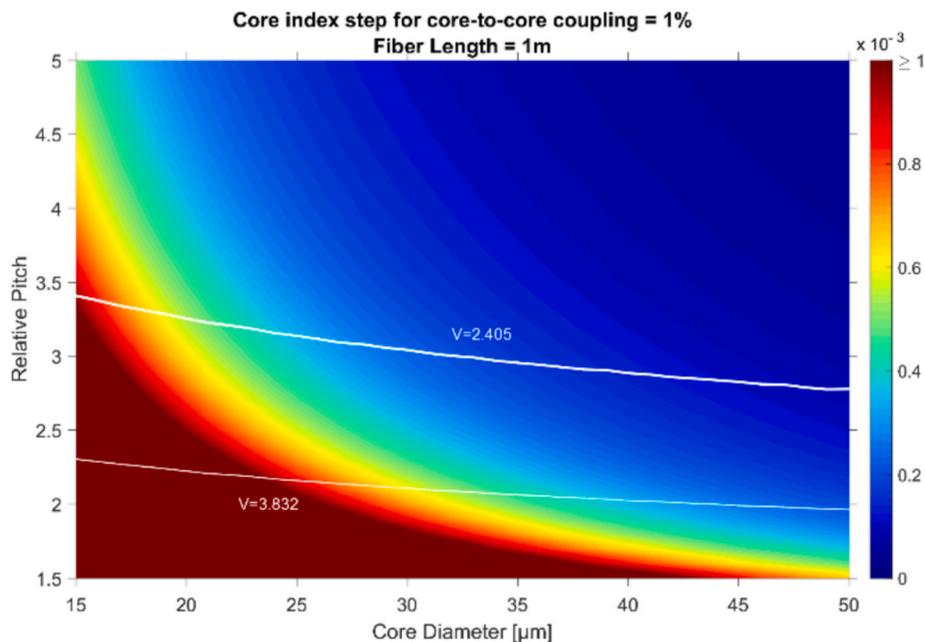

Fig. 2. Minimum required refractive index step in a 1 m long MCF (which is a typical length for a rod-type fiber) to limit coupling between next neighbor cores to less than 1 % of power. This parameter is shown as a function of the core diameter and the relative pitch (i.e. pitch-to-core diameter ratio). Iso-lines for two different V parameters are also included. Adapted with permission from Ref. [55].

Additionally, for the case of coherent beam combination with intensity beam splitters, the highest combination efficiency is achieved if all beams possess the same polarization state. It is worth mentioning at this point that even though this polarization state is in most cases linear, other states such as circular polarization, which can lower the impact of non-linearities in the fiber [64], are also possible. Moreover, even if the coherent combination of the beams is not targeted, many components behind the fiber are usually polarization sensitive. This includes optical gratings (e.g. for pulse compression) or crystals for frequency conversion. Unfortunately, it has been demonstrated that core arrangement in amplifying MCFs intrinsically causes a core-dependent birefringence due to the introduced mechanical stress [65]. This, in turn, means that, in general, the polarization state of the output beams of an MCF will be different unless measures are taken.

As it will be seen in the description of MCF-based laser systems later, it is certainly possible to work around this issue by applying and external polarization control per core. However, this introduces additional components (and adjustment effort) into the laser system, working against the targeted reduction in complexity. Besides, another effect that has to be considered is the dependence of non-linear effects on the evolution of the polarization state along the fiber. Thus, even if the output polarization from each core would be the same, the difference in the evolution during the propagation leads to a different B-Integral [64] and, with it, to a reduction of the combination efficiency [66]. Thus, polarization-maintaining MCFs are of great interest. A proof of this is that there have already been a number of publications regarding this topic [67,68].

One issue that might present itself in the design of PM MCFs is the positioning of the stress-rods [67]. Placing them between the cores, as is the usual practice, will in most cases negatively impact pump absorption which, as already mention, is problematic especially for ultrashort pulsed systems. An alternative, that poses a significantly lower penalty on pump absorption, is to put the stress-applying parts at the sides of the core array. In general, this approach will lead to lower and uneven birefringence levels across the cores, which opens the question of whether this is a viable design in practice. This is something that has been addressed in a first fiber design [68] with 5x7 cores arranged in a rectangular pattern. On each side of this arrangement, one additional row of boron doped stress-rods is added, forming a 7x7 pattern (in fact, the fiber was built using an existing design for a fiber with 7x7 cores). It is important to mention that this is a so-called rod-type fiber, i.e. a 1 m-long non-bendable fiber, which require lower birefringence levels to exhibit a polarization maintaining behavior. Based on the experimental results, a large improvement compared to a fiber with 7x7 active cores could be demonstrated, with the polarization contrast increasing from 1.5 dB to over 10 dB. However, the birefringence achieved in this case was only around 10^{-5} (instead of the 10^{-4} typical for commercial single-core fibers), resulting in a non-perfect behavior for the outer cores. In part this limitation was caused by the size and non-optimal positioning of the stress-rods. Having said that, it is to be expected that, with an optimized fiber design, a stronger and more homogeneous birefringence distribution will be achievable.

2.3. Thermal effects

Due to the difference between the wavelengths of the optical pump and output signal, a fraction of the pump energy introduced into the fiber will always be converted to heat. Additionally, effects such as absorption of the signal can further increase the temperature in the fiber. This way, the temperature distribution in the fiber needs to be always considered when operating at high average powers. This is because the temperature gradient in the fiber results in a corresponding refractive index profile due to the thermo-optical effect [69]. This phenomenon is well known in single-core fibers and related effects such as the previously described mode-shrinking [31] are well understood. In addition, a more dramatic manifestation of temperature induced refractive index

changes in the effect of transverse mode instability (TMI) [11].

The knowledge of these effects for single-core fibers can also be transferred to the individual cores of MCFs. However, the temperature and refractive index gradient that spreads across the whole fiber cross-section (shown in Fig. 3) also needs to be considered since it has a global effect on the emitted beam pattern [70]. There are two main effects that impact the combination efficiency. On the one hand, the individual beams are deformed by being pulled towards the fiber centrum, which reduces the overlap of the electric fields during the combination step. On the other hand, the light travelling through each individual core will see a core-dependent effective refractive index, i.e. a core dependent optical path length. Hence, pulses that arrive at the point of combination at the same time at low average power will see an arrival time difference at higher average powers. For coherent beam combination, this can result in a drop of the combination efficiency if these time differences are significant compared to the pulse duration [66]. In addition, the temperature profile can cause that the impact of non-linearities becomes core-dependent (same as with different polarization states during propagation), which also affects the combination efficiency. A comprehensive analysis was done in [71,72]. According to numerical simulations, the impact of the effects described above increase with the core count and the core size, as seen in Fig. 4. This figure shows a simulation of the performance scaling potential of a 1 m long, CPA, multicore fiber system (assuming 10 ns stretched pulses) in terms of average power (left) and pulse energy (right) considering effects such as TMI, mode deformation and non-linearities (B-Integral limit of 10 rad). It should be noted that the values consider the efficiency of subsequent coherent beam combination. As can be seen, MCFs with more than 6x6 cores and moderate core sizes (30 μm to 50 μm) can potentially operate at average powers in excess of 10 kW. This value can be in principle increased if longer fibers are considered. The deviation from a perfect increase of average power with the core count (and the dependency on the core size) can be explained by the reduction of combination efficiency due to the mode deformations mentioned and a maximum temperature limit set to 500 °C. In terms of pulse energy, the simulation predicts operation at multi-100 mJ level with the large cores (50 μm to 80 μm). Theoretically, a perfect scaling with the active area (given by core size and number of cores) can be expected. However, reasonable repetition rates (between 10 kHz and 100 kHz) were assumed in the simulation. Again, mode deformation reduces the combination efficiency and additionally increase non-linearities, requiring a reduction in per-core pulse energy. A later publication presented some optimization strategies that should allow further improving this expected performance by reducing the impact thermal effects [73].

3. State of the art of multicore fibers and systems for performance scaling

The MCF is only one part of a complete laser system, and its actual performance depends on a large number of different components. Therefore, in this section the performance of complete MCF systems will be reviewed. However, at this point it is necessary to make a distinction since such systems are usually specialized either to achieve the highest possible average power (mostly using long and flexible fibers) or to deliver high pulse energy/high peak powers (mostly using short, rod-type fiber designs). In the following such systems will be reviewed separately.

3.1. Average power scaling

There have been several MCF laser systems presented over the last years. Some of the earlier ones demonstrated coherent beam combination with femtosecond pulses using a 49 core fiber and a 7 core fiber and were published in 2010 [74] and 2015 [67], respectively. In both publications, spatial-light-modulators (SLMs) were used to split an incoming beam into 49 or 7 sub-beams. While the first fiber used cores with 2.5 μm
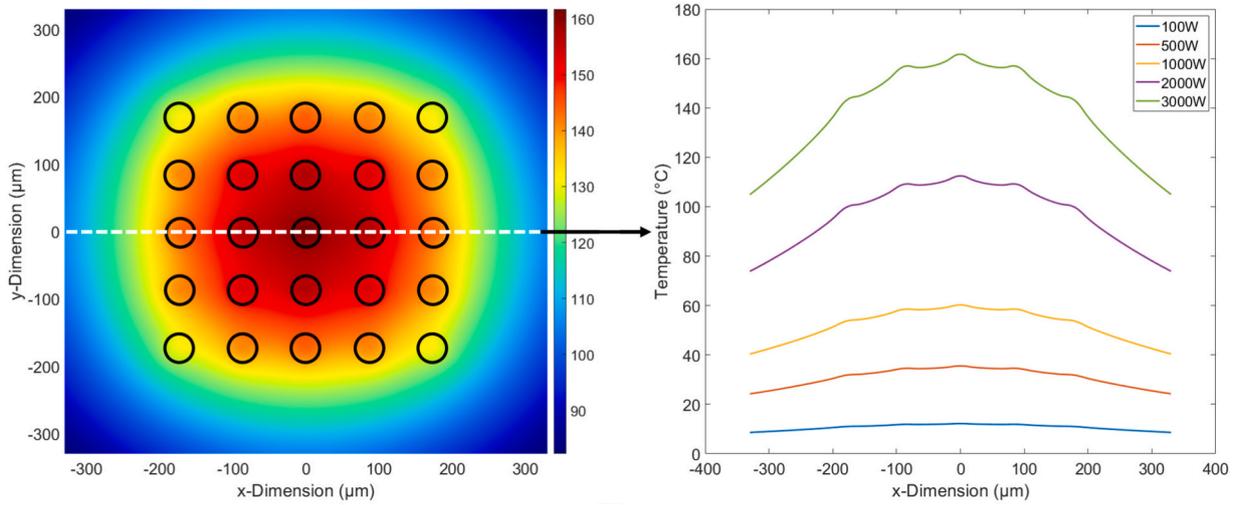
Fig. 3. Left: Temperature profile at the output of a 1 m long 5x5 MCF with 30 μm cores operated at 3 kW average power. Right: cross-sectional temperature profile depending on the average power.
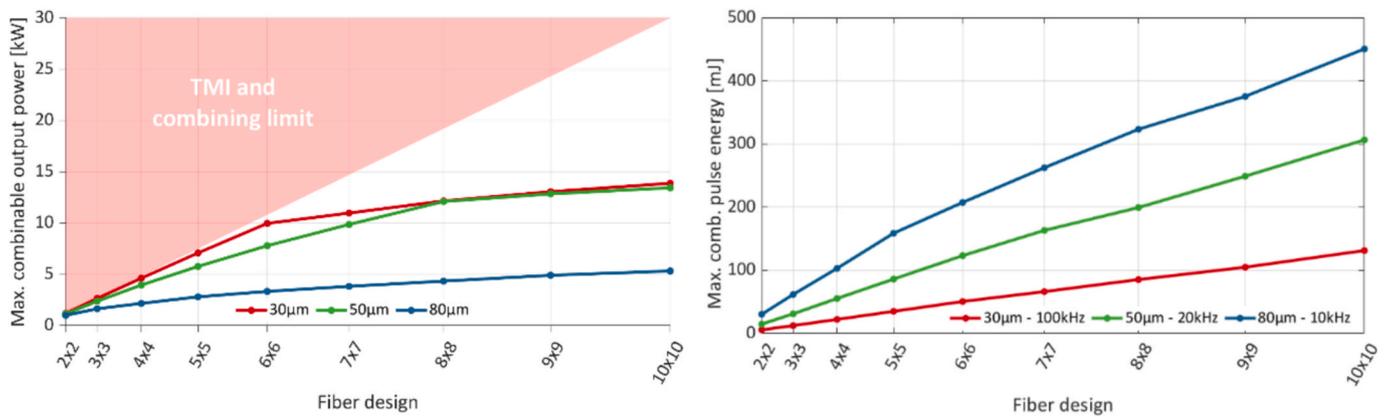

Fig. 4. Maximum achievable coherently combined average power and pulse energy for a 1 m long MCF with 3 different core sizes and different number of cores. A femtosecond CPA regime with pulses stretched to 10 ns was assumed. TMI, mode deformation and non-linearities were considered in the calculations. Adapted with permission from Ref. [70].

diameter, the second one already employed cores with 16 μm mode-field diameter. The second fiber also incorporated stress-inducing boron elements for polarization maintenance and an air-clad for pump guiding. In the corresponding experiment, tiled-aperture beam combination was realized with 49 % of the output power in the central lobe (compared to 76 % considering perfect combination both in the spatial and temporal domains). This way femtosecond pulses with up to 2.6 W power could be achieved, and pulse energy scaling in comparison to using just a single-core could be demonstrated.

Since then, the performance of these fibers has rapidly improved. For example systems with flexible fibers with 16 [75] and 6 cores [76] were presented in 2018 and 2023, respectively. In the first case, a 5 m fiber with 19 μm cores arranged in a rectangular array was. An output power of 70 W for picosecond pulses and 205 W for stretched femtosecond pulses [77] could be achieved. The efficiency of the filled-aperture coherent combination process was 80 % in both operation regimes and, in the latter case, the combined pulses could be compressed back to 480 fs duration (Fig. 5). Additional average power tests were conducted, reaching up to 1.4 kW total average power. The other flexible MCF had 6 cores arranged in a ring near the fiber edge to minimize thermal impedance, according to the authors. The cores had a diameter of 15 μm each with a cladding size of 680 μm, and the fiber length was 8.5 m. The authors of that work built an all fiber system using this MCF that delivered a total output power of up to 1.2 kW. An individual
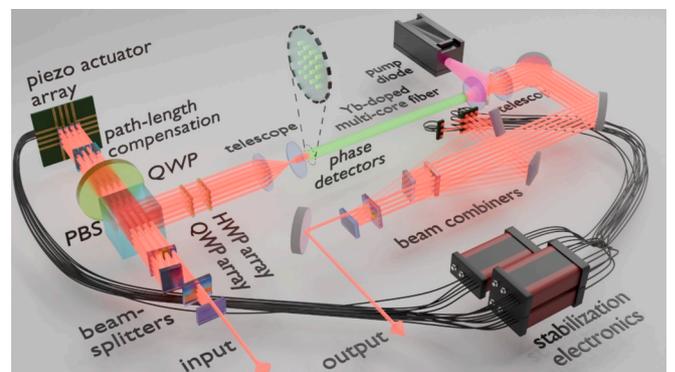

Fig. 5. Schematic setup of an MCF amplifier configuration for coherent combination, including splitting and combination elements (SMS elements), phase stabilization detection and actuation as well as half- (HWP) and quarter-waveplate (QWP) arrays to compensate for the non-polarization-maintaining behavior of the MCF.

characterization of the beam quality emitted by the cores was also done, with values ranging between $M^2 < 1.4$ and < 2.2.

As can be seen, multicore fibers have now shown more than 1 kW of

total average power in experiments. Based on the simulation results shown in Fig. 4, even a 1 m long fiber should be able to surpass 10 kW average power for more than 36 cores, if enough pump power is available. Hence, for longer fibers, even higher values can be expected as the heat load can be distributed over the length, e.g. 100 kW for a 10 m long fiber. Even though this prediction is strictly speaking valid when only considering thermal effects, we believe that it can still be valid for pulsed systems under some circumstances. In this context, when considering non-linear effects for pulsed laser systems (e.g. SPM or Raman), this projection is still valid if the number of cores is sufficiently high. For example, it is known that single-core average powers of 1 kW have already been demonstrated experimentally for CW and ultrafast systems [41]. Thus, considering a MCF with 10x10 cores, it seems realistic to predict a performance of ~ 100 kW. In any case the total average power level that can be achieved by MCFs certainly surpasses current projections about what will be theoretically be possible with single-core fibers [78], which is around 30 kW in the best case.

3.2. Pulse energy scaling

As already mentioned, rod-type fibers are preferred for energy scaling, as they enable larger core diameters together with a short length (which efficiently mitigates non-linear effects). In this respect, there have already been different rod-type MCFs presented over the years. In 2008, a Q-switch oscillator based on a 6-core MCF was realized with each core having a diameter of 40 μm and based on the photonic-crystal-fiber concept [79]. Pulse energies of 2.2 mJ with 26 ns duration at 10 kHz repetition rate were achieved. It should be noted that this fiber was in-fact based on coupled cores. In [63], a fiber with 4 cores based on a photonic-crystal core design could show the scaling of the TMI threshold with the number of cores. In this experiment a single core reached the TMI threshold at around 150 W, whereas operation with all four cores simultaneously led to a threshold of 536 W. However, due to the low beam quality of the beams emitted by this fiber, it could not be used for coherent combination.

A rod-type fiber with 4x4 cores (see Fig. 1) was used in a similar setup as the flexible one described above. This fiber had a pump-cladding delimited by an octagonal fluoride-doped ring, thus allowing for an all-glass structure. The MCF used in this experiment had core diameters of 21 μm and could operate single-mode, thus making them suitable for coherent combination [80]. Here, an average power after combination (with an efficiency of up to 85 %) and compression of 500 W at 10 MHz repetition rate was achieved using double-side pumping. Additionally, by reducing the repetition rate to 687 kHz, a pulse energy of up to 600 μJ was demonstrated. At this point it should be noted that non-linear polarization rotation [81] was observed in this case. This adds an additional change of polarization of the output beams on top of the one caused by the intrinsic birefringence described in the previous section. To compensate both effects, two arrays consisting of half- and quarter-waveplates were added in front of the fiber to optimize for a linearly polarized profile at the fiber output. The beam-splitting and combination stages comprised segmented-mirror-splitters (SMS) [82] and the phase control was done with a 4x4 piezo array with attached mirrors. The detection of phase differences between the individual channels was achieved by measuring the non-combined power in the different beams reflected from the SMS and using a sequential phase locking algorithm [83]. Very low residual power fluctuations of 0.3 % RMS could be detected with this stabilization setup.

To further explore the energy scaling opportunities offered by MCFs, 4x4 fibers of the same type as that described above but with larger core diameters were employed. The nanosecond seed source was a Q-switched, 4x4 MCF (similar to the one described above) operated with a Pockels-cell and emitting 30 ns pulses. The output beam array of the seed could then be directly coupled with a single telescope into the main amplifier MCF. Here two 4x4 MCFs were tested: one with 50 μm core diameter and a tapered one which cores have 19 μm in the small end 50 μm in the large end. Using this setup 49 mJ output pulse energy could be achieved with the first MCF, and 37 mJ with the tapered MCF [84] (which showed a drastically increased beam quality compared to the untapered MCF, something also known from single core fibers [85]). After adding a LBO crystal, it was also possible to convert the output beam array to 515 nm wavelength via second-harmonic generation (SHG) [86] to a total pulse energy of 17 mJ with more than 50 % efficiency. As it will be described in the outlook, such a laser system might be employed as a very efficient driver for the optical pumping of Ti:Sa lasers.

Recently, work has been done to further increase the channel count in MCFs. Increasing the number of beams also requires a scalable implementation of the phase detection and actuation systems. In fact, the authors of this paper believe that these added demand on the detection and control methods will be an important topic for these systems going forward. In order to meet this challenge, most of the signal processing, which was previously implemented in hardware (e.g. modulation and demodulation of phase dithers), was moved to a software-based implementation running on a PC. Together with a MEMS array, which can nowadays have thousands of mirrors, this provides a very scalable but compact system. Additionally, this particular implementation also provides a global overview about the whole system and not just individual channel information. With these implementations in place, a rod-type fiber with 7x7 step-index cores was used in the system (shown in Fig. 1). This fiber has an air-clad for pump guidance, as this enables a higher NA of the pump radiation, i.e. pump diodes with a lower brightness but higher average powers can be coupled in. Additionally, for convenience, the pre-compensation of the polarization changed induced by structural birefringence was done with a spatial-light-modulator [87]. In this experiment, again fibers with different diameters were used for the coherent combination of femtosecond pulses (25 μm core diameter) and the generation of high-energy nanosecond pulses (> 30 μm core diameter). In the context of ultrashort pulse operation, a pulse energy of up to 1.75 mJ was achieved, which corresponds to factor 3 more energy than that obtained from the 4x4 fiber, i.e. the increase in pulse energy matches the increase in the core count. A combination efficiency of up to 80 % could also be demonstrated, with the non-combining residual power mostly consisting of higher-order mode content [88].

For the energy scaling experiments, a 7x7 fiber with 30 μm core diameter was used. It is worth pointing out that, even though each core is smaller than those employed in the experiment with a 4x4 MCF, the large increase in channel count overcompensates for this and still provides a net energy scaling opportunity with the promise of a good beam quality. This way, a maximum total pulse energy of 110 mJ was achieved with average powers of up to 500 W [89]. These experiments showed that up to 75 % of the stored energy in the fiber could be extracted. Additionally, a very high stability of the emitted energies of 0.2 % RMS could be achieved. First experiments regarding SHG generation also showed very promising results with conversion efficiencies > 50 %, following the results of the 4x4 fiber [90].

In summary, MCF laser systems have rapidly evolved from some early very promising experiments at comparably low average power and pulse energies, to systems that can now compete with coherently combined systems consisting of multiple single-core fibers, emitting kW average powers and mJ energy femtosecond and J-class nanosecond pulses (Table 1). However, in comparison to them, in MCF systems the component count and footprint can be dramatically decreased. For example, a reduction of a factor of 6 reduction in the absolute component count and footprint when comparing a coherently combined 4x4 MCF system with a 16-channel system based on single-core fibers is estimated. Moreover, the component count and footprint do not significantly change when substituting the 4x4 MCF with the 7x7 MCF in the system. This bodes well for a future increase in channel count. Additionally, it should be noted that the vast majority of the MCFs that have been employed by research groups around the world so far are based on

Table 1

Overview of selected laser systems based on MCFs with their fiber and output parameters.

Year	Number of cores	Core diameter / μm	Emission type	Average power	Pulse energy	Reference
2008	6	50	Nanosecond pulses	22 W	2.2 mJ	[79]
2010	49	2.5	CW	Not stated	N/A	[74]
2015	7	16	Femtosecond pulses	2.6 W	260nJ	[67]
2018	16	19	Nanosecond pulses	1.4 kW	140 μJ	[77]
2022	16	21/50	Femtosecond pulses/Nanosecond pulses	500 W/49 W	600 μJ/49 mJ	[80,84]
2023	6	15	CW	1.2 kW	N/A	[76]
2024	49	25/33	Femtosecond pulses/Nanosecond pulses	260 W/500 W	1.75 mJ/117 mJ	[88,89]

a step-index core design. This naturally limits the maximum core diameter and, thus, the extractable energy. Hence, the implementation of advanced core designs will be a task in the future, which is expected to transform MCF laser systems into the most powerful fiber laser technology, enabling multi-kW average powers with J-class pulse energies.

4. Multicore fibers – Beyond power scaling

The laser systems described in the previous chapter employed MCFs for power/energy scaling. However, control over the individual emitters of an MCF can also be used for temporal and spatial shaping of combined output beams and pulses. To counteract gain narrowing during the amplification process, it has been proposed to amplify different spectral components of a broadband pulse individually, followed by recombination. This spectral combination concept has already been demonstrated for individual fibers [91]. It is expected that a higher channel-count will offer more granular control about the spectral properties, which makes MCF a very attractive technology for this approach. In fact, different experiments have been conducted with 12-core Ytterbium-doped fibers [92,93]. After optimization of the output phases for the different spectral components, pulse durations as short as 100 fs could be achieved with a bandwidth of 40 nm. The use case of this concept might not be limited to achieving the shortest possible pulse (thus, the highest possible peak power) but potentially enable dynamic and application adapted temporal pulses shaping.

MCFs can also be employed for spatial beam shaping, akin to what was successfully demonstrated for the coherent combination of individual fiber amplifiers [44,45]. This way, phase control of the individual emissions can, for example, enable the generation of optical-angular-momentum beams (OAM) [94]. So far, these beams have been generated by using static conversion elements in the laser beam [95], as done e.g. for the generation of circularly polarized attosecond pulses through higher-order-harmonics [96]. However, phase actuators based on the electro-optical-effect, i.e. EOMs, are currently available with speeds in the GHz range which makes pulse-to-pulse control of the individual beams possible. Therefore, with the use of coherent beam combination, structured beam profiles can now be dynamically generated. For example, in [97] a 7 core Er:Yb MCF was used to demonstrate structured-light generation. Using an SLM as both the phasing and polarization control element, the generation of scalar LP modes as well as vector beams was demonstrated.

This approach can also be applied to the system based on the 7x7 MCF described in the previous chapter. By replacing the SMS element with a mixed-aperture beam-splitter [98], the pulses emitted by the MCF arrive at the same time at the combining plane, which is a pre-condition for tiled-aperture combination (see Fig. 6). The phase control software was updated to maximize the power at the center with the SPGD algorithm [99]. This resulted in a typical tiled-aperture beam profile with the highest intensity in a central lobe and some side lobes. The beam array is combined after the pulse compressor, achieving pulses with an auto-correlation duration of 460 fs and average powers of 150 W. In addition, some preliminary experiments show that the generation of OAM modes is also possible in this configuration, albeit with a rather high amount of energy contained in the side lobes. Further investigations on this topic are planned.

In summary, the topic of temporal pulse and beam shaping with MCFs is still quite novel, but the published experimental results have certainly already unveiled the potential. The ultrafast dynamic beam shaping systems can be employed for various scientific and industrial applications, such as materials processing to overcome limitations due to heat accumulation [100] or producing X-rays using nanoparticles [101]. Combining the presented temporal and spatial shaping mechanisms will potentially allow dynamic control about the electric field of the laser in all 3 dimensions.

5. Multicore fibers – Outlook and applications

In the previous chapters, some basic considerations about amplifying MCFs were discussed and the state-of-the-art, including laser system performance, was reviewed. As already shown, a rapid development of this technology over the last decade could be observed. However, there is still a considerable gap between the potential performance predicted by theoretical simulations (i.e. 1 m long fibers emitting multi-kW average powers) and the current performance values demonstrated with these fibers. This gap will have to be bridged in the next years. Part of this effort will include the integration of large-area advanced core designs into MCFs to scale the energy extraction per core to the level of the most powerful single-core fibers. As shown in Fig. 4, a MCF with 10x10 80 μm cores could provide femtosecond pulses with 500 mJ energies, competing regarding this parameter with thin-disk based systems [102]. Additionally, it is expected that the choice of active material is expanded from Erbium and Ytterbium (at present) to Thulium and
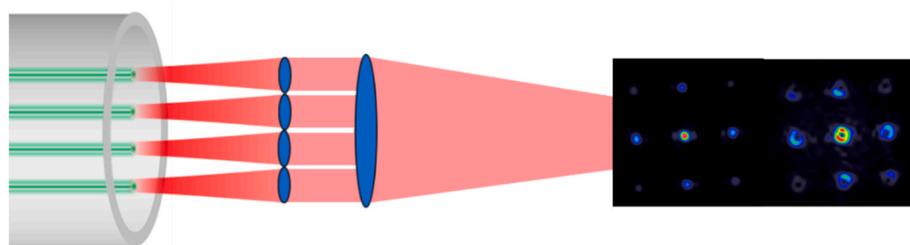

Fig. 6. Schematic setup of tiled-aperture beam combination of the beams emitted by an MCF. If the output beams are in phase, the power in the central lobe is maximized (with additional side-lobes appearing due to the low fill-factor of the beams). By controlling the phase of the individual beams, a vector beam can be generated.

Holmium, which emit at around 2 μm. In fact, operating around 2 μm can bring tremendous advantages for many applications such as materials processing of silicon and plastics, the generation of HHG in the water-window region or the generating of mid-IR radiation at high average powers.

Talking about laser systems based on amplifying MCFs would not be complete without taking potential applications into account. In general, it can be said that all applications that require or can benefit from higher average powers/pulse energy will profit from this development. This includes applications that are already addressable today, such as the generation of coherent light in the XUV wavelength region (e.g. for imaging [103] and spectroscopy [104,105]), plasma-based X-ray sources [106] or materials processing. As an example, when used as a driver for secondary radiation, the increased average power available with MCFs results in a corresponding increase of the photon flux, reducing acquisition times for imaging. However, the high pulse energy that MCFs can potentially deliver (which is a new territory for fiber lasers) make these fibers also extremely interesting for applications that are so-far only addressable with other laser technologies. One example is the optical pumping of Ti:Sa lasers, which due to their high pulse energy and short pulse durations are a technology employed for laser particle acceleration. Here optical pumping can be addressed by a pulsed, frequency doubled 1 μm source [107]. With total energies higher than 0.1 J (for nanosecond pulses) now available from an MCF [89], and a roadmap for scaling it to the multi-Joule regime with larger core diameters and a higher core count, MCFs might be a good alternative to current pump technologies. Looking even further, direct drive of laser particle acceleration might be pursued, but will in addition to the power scaling require additional investigation of aspects like the temporal pulse contrast of MCF based systems [108]. Another possibility is the generation of EUV light, for example for the semiconductor industry. Laser driven sources at 2 μm are currently seen as a promising driver for EUV generation [109]. In this context, thulium-doped MCFs, with their promise of high energy and average power, can be a tantalizing choice for this and other visionary applications. Finally, the previous chapter showed the temporal and spatial shaping possibilities that can be enabled by phase (plus amplitude and polarization) control of the MCF emission. Fast actuators can provide a per-pulse modification of the electric field in all 3 dimensions, dynamically adapting to the target application.

CRediT authorship contribution statement

Arno Klenke: Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cesar Jauregui:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mehran Bahri:** Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Johannes Nold:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Stefan Kuhn:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Nicoletta Haarlammert:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Thomas Schreiber:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Jens Limpert:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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