Technological advances in pulsed fiber amplifier systems

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Fiber amplifier systems open up the possibility of highly flexible pulsed laser sources with characteristics that can be tailored exactly to the application requirements. With a chain of fiber amplifiers, repetition rate and pulse duration can be varied over a wide range without affecting beam quality.

Pulsed fiber lasers and amplifiers have industrially matured to deliver tens of kilowatts of peak power in a diffraction limited beam. In addition, the architecture of the fiber laser also enables a high flexibility of pulse parameters at constant beam quality due to the confinement of the laser mode by the index profile of the fiber. The laser mode of all other solid state lasers depends also on the overlap of pumped volume and laser mode volume. Varying pump powers or changes of the extracted laser energy result in a different thermal load of the laser crystal. This changes the thermal lens of the laser crystal, which may result in a varying laser mode depending on the laser parameters.
On the other hand, fiber lasers require pump diodes with good beam quality for efficiently launching the pump light into the pump cladding waveguide. This represents an economic trade-off of high average power fiber lasers with other solid state lasers requiring pump diodes with lower beam quality.

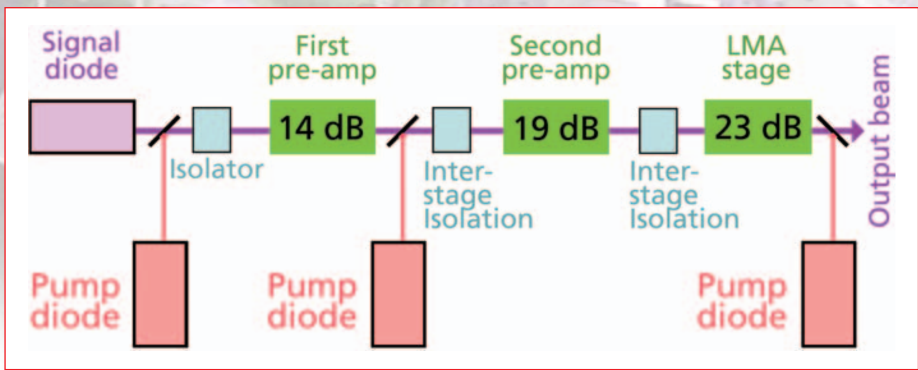

Figure 1*: Schematic set-up of a master-oscillator all-fiber laser system*

1 LMA fiber technology for high pulse energy

Over the last few years innovations in fiber design, coupled with improvements in fiber manufacturing, have enabled fiber based lasers and amplifiers to achieve higher and higher power levels. A critical development has been large mode area (LMA) fibers with a core diameter greatly increased to around 30 µm. Their mode field diameter (MFD) is ~24 µm at 1060 nm, as compared to conventional telecom fibers with a MFD of ~6 µm. This substantially increases the attainable peak power before deleterious effects such as non-linear scattering and optical damage reach their threshold.
Of critical importance is the ability of these fibers to deliver single-mode beam quality despite the fiber's capability to support multiple transverse modes [1, 2]. Techniques for enabling fibers to exhibit this behavior have been demonstrated in lab based environments for several years and coupled with the availability of good quality fiber are now beginning to appear in products ready for industrial and military applications.
Indeed "standardization" of LMA fiber technology has matured to the point where many critical components are now available with LMA compatible fiber pigtails, for example modulators, isolators and couplers/combiners for industrial laser systems. Further evidence of standardization is the availability of certain LMA fiber designs from multiple fiber vendors.

2 Pulsed fiber amplifier architecture

The design of pulsed fiber amplifiers is guided by the demand for a diffraction limited beam with maximum flexibility of pulse duration, pulse shape and repetition rate. Furthermore, the pulse energy must be maximized to cover a broad range of applications and the system should be monolithic. A configuration of seed laser and fiber amplifiers fulfills these requirements and allows for an efficient monolithic laser system. The pulse duration of such a system can be continuously adjusted from several nanoseconds to continuous operation, with repetition rates ranging from several Hertz to 1 MHz, and pulse energies reaching 0.5 mJ in the example given in 3.1. The schematic of such a set-up is shown in **figure 1**.
A single-mode diode laser can be used for seeding several amplifier stages. Single-mode, single-clad fibers and corresponding components are used, as long as the peak power is not approaching the threshold of non-linear effects, such as Raman or Brillouin scattering, or optical damage. Therefore, further down line, LMA fiber is mandatory. The required pulse energy and pulse duration define the number and the design of the individual amplifier stages.

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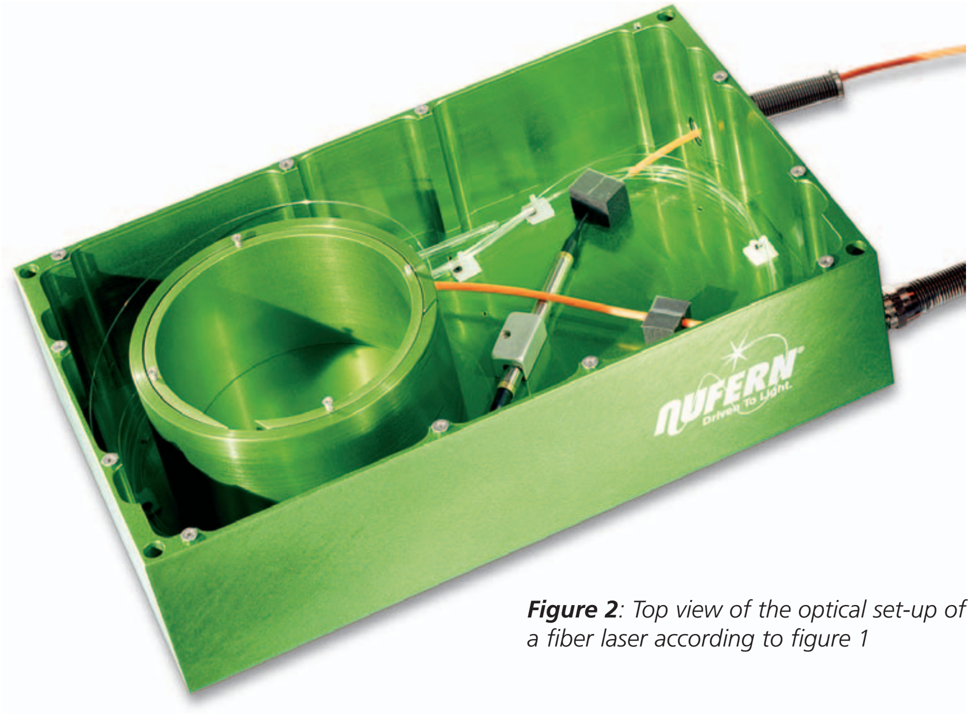

***Figure 2**: Top view of the optical set-up of a fiber laser according to figure 1*

2.1 Example of a fiber amplifier design

In the set-up shown in **figure 2**, a seeder diode is used that emits 150 mW maximum average power. It is frequency stabilized by a Fiber Bragg Grating (FBG) to emit at 1,064 nm. A monolithic wavelength division multiplexer (WDM) combines the seeder diode emission with the beam of a single-mode pump diode, launching both wavelengths into one end of a single-mode single-clad active fiber with 6 µm mode field diameter (MFD), 125 µm cladding, and approximately 4 m long.
An optical isolator is arranged between the seeder diode and the active fiber to minimize feedback from the amplifier fiber into the seed laser diode. The pump diode emits 300 mW at 980 nm, limiting the first pre-amplification to about 14 dB (10 kHz, 8 ns) with the peak energy well below the threshold for nonlinear effects. An optical isolator, a bandpass filter, and an acoustic-optical modulator are placed at the exit of the amplifier fiber. The latter two components eliminate feeding amplified spontaneous emission (ASE) back into the active fiber from subsequent amplification stages.
An identical amplifier stage, pumped with a 500 mW single-mode diode laser, is arranged as a second pre-amplifier. So far, the total amplification of the signal of the seeder diode is approximately 33 dB (10 kHz, 8 ns), from 40 mW peak to about 100 W, equivalent to amplifying 0.4 nJ pulse energy to 1 µJ. The set-up is all monolithic and the diffraction limited beam is unpolarized – or also polarized, if proper polarization maintaining fibers (**figure 3**) and components are used.
The pulse energy limit of single-mode single-clad fibers is approximately 48 µJ and therefore, further amplification requires large mode area (LMA) fibers. A tapered fiber allows the transition from the small to the large mode area without exciting additional modes in the LMA fiber. This enables a monolithic set-up without the need for coiling the fiber for mode discrimination. An active dual-clad LMA fiber with 30 µm core, 250 µm cladding, and approximately 5 m long was used and pumped with 30 W at 976 nm from the output end of the LMA fiber. 23 dB amplification (10 kHz, 8 ns) are achieved in the LMA fiber, resulting in 200 µJ pulse energy and 2 W average power.
Pulse energies up to 500 µJ are feasible with this fiber before approaching the load limit of this particular LMA fiber. However, for high repetition rates of 100 kHz and more, average powers of up to 20 W are possible, as discussed in the following section.

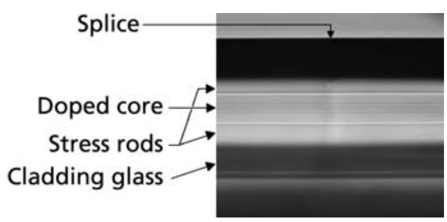

***Figure 3**: Thanks to more suitable splicing machines, PM-LMA fibers with large cladding diameters can now be spliced quite easily. Since then, double clad polarization maintainig fibers have become more readily applied to high power PM fiber amplifiers*

3 Results of recent pulsed fiber amplifier experiments

A system as described above, but with polarization maintaining fiber (such as in **figure 4**) and components, was characterized for different pulse settings. The polarization extinction ratio was measured to more than 17 dB and no changes of direction of polarization could be observed. The peak power was measured after each amplifier stage for 10 kHz and 100 kHz repetition rate for 8 ns long pulses as shown in **figure 5**. The resulting peak power decreases from 20 kW at 10 kHz to 5.5 kW at 100 kHz.
By increasing the repetition rate, the amplification of each single-mode, single-clad amplifier stage decreases by about 1 dB, whereas in the dual-clad LMA fiber the amplification at 100 kHz is 3.3 dB below the 10 kHz values (**figure 6**), which simply reflects the higher saturation for this power amplifier stage. Aside from amplification - when looking at average powers, the system provides 7 W at 10 kHz and even 20 W at 100 kHz.
The caustic (**figure 7**) revealed circular geometry, but was measured to result in a relatively "bad" beam parameter product M^2 = 1.42. Multiple imperfect surfaces attenuating the beam and a molded aspherical lens used for collimation are the main reasons for the imperfect beam quality measured. Obviously when deployed the system would utilize a better quality lens.

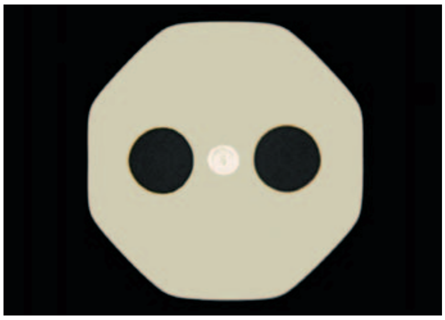

***Figure 4**: Cross section of polarization maintaining fiber with strain elements left and right alongside the fiber core and octagonal pump cladding for improved pump power coupling*

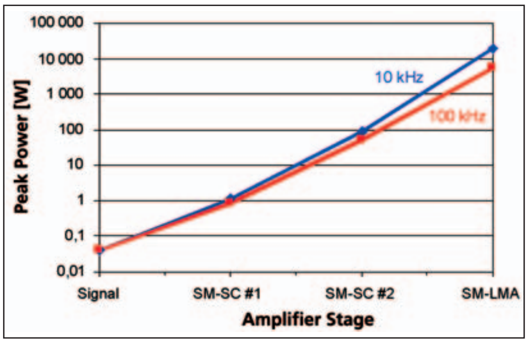

***Figure 5**: Peak power at 10 kHz and 100 kHz repetition rate for 8 ns pulse duration, measured after the subsequent amplifier stages of the monolithic fiber laser system (SM-SC=single-mode single-clad active fiber of the two pre-amplifiers). The pulse energy [µJ] can be obtained for both repetition rate graphs by dividing the power by 125 (i.e.multiplication with 0.008 µs pulse duration)*

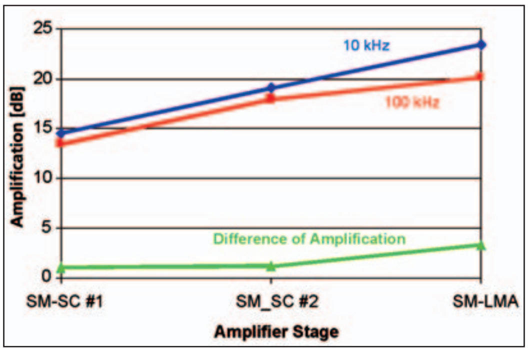

***Figure 6**: Amplification for 10 kHz and 100 kHz repetition rate for 8 ns pulse duration. Also shown is the difference in amplification, which is characteristic to the two different fiber designs used in the system*

suitable for transfer to industry qualified products. Such fiber research also extends to novel waveguide designs [4,5].
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4 Applications

The flexible pulsing characteristics at constant beam quality make this type of laser an interesting tool for a variety of applications. LIDAR (Light Detection and Ranging) and LIPS (Laser Induced Plasma Spectrometry) both can enhance their sensitivity greatly with tailored pulse shaping and burst mode operation. LIDAR and LADAR ("Laser-Radar") further benefit from the stable polarized output allowing polarization sensitive measurement for further improving the signal to noise ratio.
Power and energy of the demonstrated system are sufficient for high quality marking of many different materials, however these are typical high throughput applications with mostly fixed laser parameters for which simpler laser set-ups can be sufficient. But precision micro-machining can greatly benefit from the flexible fiber laser system with excellent beam quality. Applications range from the drilling of high precision, high aspect ratio holes with tailored cross section at even angled surfaces to cutting and welding. For drilling, about 1.5 µJ are required within pulses of several nanoseconds and either percussion or trepanning is used. Micro-welding is done with either long pulses, several microseconds or even milliseconds long, or by switching the system to continuous operation. The specific setting of the laser parameters depends on the material, joint design and product. Pulsed welding is typically used to minimize the heat input and thus distortion of the welded part, while continuous welding is applied for maximum throughput. Power ramping and pulse shaping are always required.

5 Present limitations, and outlook

Currently, standard off-the-shelf LMA fibers are commercially available with core diameters up to ~30 µm. Such fibers are well optimized to deliver good beam quality in robust configurations suitable for product development as demonstrated in this article. However, the limitations to these fibers in terms of non-linear effects and damage threshold, rule out many interesting applications at higher pulse energies, where e.g. mJ level pulses in the single ns regime are required, approaching MW peak powers.
For these applications, fibers with larger MFDs have been manufactured and indeed have demonstrated, at least in lab based experiments, excellent beam quality into the mJ level (see [3] for a review). Currently the goal of much research is the development of this new class of LMA fiber lasers capable of delivering robust single mode beam quality at higher pulse energies, and

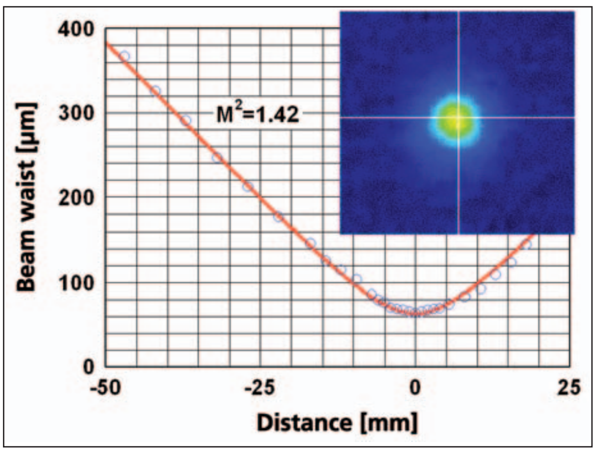

***Figure 7**: Beam quality of the flexible pulsed fiber amplifier. Using a higher quality lens and abandonment of beam attenuation would improve beam quality significantly*

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