SINGLE CRYSTAL FIBER FOR ULTRASHORT PULSES LASERS

Abstract: Driven by the micromachining industry, where short pulses mean precision and power equals process speed, short pulse width high power lasers are in high demand. Whereas the MOPA (Master Oscillator Power Amplifier) is the current preferred architecture, it still suffers from performance limitations and high costs associated with system complexity and power amplifier limitations.

A new amplifier technology based on single crystal fibers (SCF) is described; its benefits and the implementation in a complete ultrafast laser system are detailed.

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INSTITUT d'OPTIQUE GRADUATE SCHOOL ParisTech

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SINGLE CRYSTAL FIBER FOR ULTRASHORT PULSES LASERS

In material processing, short pulses translate to precision and accuracy while high average power leads to higher processing speed with high energy providing processing capability. Short pulses can be readily achieved but high average power for short pulses is more difficult. A well accepted solution to achieve high power in a short pulse width laser is a MOPA architecture using various techniques and materials for the amplification. Bulk crystals amplifiers suffer from beam degradation due to the strongly aberrant thermal lensing effect created inside the material. Because of this fundamental limitation, high power amplifiers evolved in several directions to better manage the heat inside the gain medium: thin disks, slabs and special fibers.

Because of the limited gain in a single pass, thin disk amplifiers require a high number of passes or a regenerative amplifier to reach high power, leading to complex and costly systems. High gain is achieved in slab amplifiers leading to very high average power, up to the kW level, but the complex path of the amplified laser can introduce beam ellipticity and degraded beam quality. Fiber laser amplifiers for short pulses use LMA (Large Mode Area) fibers to reach high average power with a good beam quality but are limited in peak power due to non-linear effects. Chirped pulse amplification alleviates this limitation but adds to the complexity and cost of the system.

Today, SCF (Single Crystal Fiber) amplifiers closely approach the ideal for short pulse amplification. A single-crystal fiber (SCF) is a single-crystal with a long length, a small diameter and attractive light guiding properties. Those guiding properties can be used in a straightforward end-pumping configuration to guide the pump radiation inside a single-crystal laser medium (see Fig. 1). These new devices produce high intensity, linearly polarized laser light with superb beam quality and adjustable repetition rate. Fibercryst and the Laboratoire Charles Fabry of the Institut d'Optique (CNRS-LCFIO) worked together for 10 years to develop and optimize this technology.

SINGLE CRYSTAL FIBER PUMPING

Single crystal fibers are typically 1 mm in diameter and 30 to 50 mm long. They are generally produced in Nd:YAG or Yb:YAG. For ultrashort laser systems, Yb:YAG is preferred because of its larger bandwidth and the lower cost of 940 nm pump diodes. In a SCF amplifier, the laser beam is unguided through the crystal, like in a classical rod, with a typical diameter of 400 µm at $1/e^2$. The high refractive index of the crystal naturally limits the divergence of the beam.

The pump beam is focused In a 400 µm diameter spot near the crystal fiber input. The highly divergent beam is then guided by total internal reflection and refocused again in the gain medium.

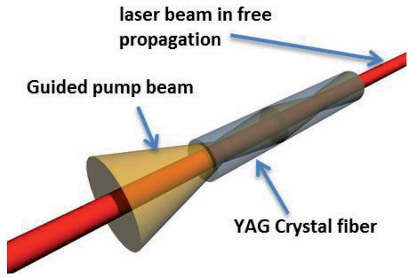

Figure 1: *Principle of SCF amplifier*

The initial focusing point of the pump is imaged several times along the fiber length, depending on the pump brightness.

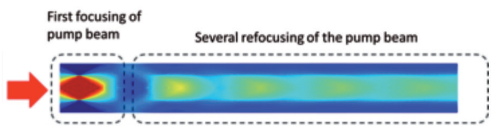

Figure 2: *Example of pump propagation*

The pump beam is kept collinear to the laser beam during the propagation in the gain medium, avoiding off-axis aberrations that can appear in slabs or thin disks such as astigmatism, therefore leading to superior beam quality.

The doping is typically one order of magnitude lower than in usual bulk crystals, and the length typically one order of magnitude higher. Without pump guiding, this would be useless because of the high divergence of the pump. But combined with pump guiding, this long length/low doping rate ratio enables to dispatch the pump absorption along the entire crystal fiber length and therefore to lower thermal stress in the gain medium.

SINGLE CRYSTAL FIBER AMPLIFIERS

Thanks to their high gain and excellent management of high powers, Single Crystal Fibers are perfectly suited for MOPA (Master Oscillator Power Amplifier) configurations. This configuration has already proven its efficiency and flexibility in the field. In practical term, Yb:YAG SCF gain modules produced by Fibercryst were pumped up to 600 W at 940 nm without damage [1], far above the typical pumping level of usual bulk crystals.

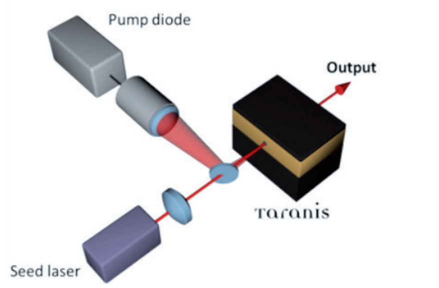

Figure 3: *Amplifier setup with SCF integrated into a Taranis Module supplied by Fibercryst*

Cooling a 1 mm diameter YAG rod submitted to hundreds Watts of pump is not an easy challenge, but this issue was solved by the development of the Taranis module, a technology patented by Fibercryst and the CNRS-LCFIO lab to integrate the crystal fiber directly into a metallic mount. The achieved cooling is very efficient, with a thermal exchange coefficient up to 5 W/cm²/K, 5 times better than classical indium pressed solutions.

Figure 4: *Water cooled Taranis Module*

The thermal gradient in the pumped crystal fiber is also radially symmetrical, to guarantee once again an excellent beam quality even at high power. High average power of 140 Watt has been achieved without reaching the limit of the SCF technology [2].

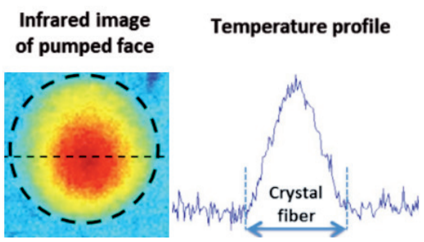

Figure 5: *Thermography image of a pumped SCF module*

HIGH GAIN AND HIGH PEAK POWER

In a classical Large Mode Area (LMA) fiber amplifier, gain of 20-30 dB can be achieved with extraction efficiencies around 50-60%, but the maximum peak power is generally limited below 1 MW by the small surface of the core (typically 0.001 mm²). This is due to non-linear effects like SPM (Self Phase Modulation) or Raman which quickly appear when high peak intensities are propagated in such small surfaces.

At the opposite, in usual thin disk amplifiers, very high powers can be achieved but the gain is typically limited around 10 or below.

In a SCF amplifier, the surface covered by the laser mode is typically 100 times higher than in LMA. Thanks to that, peak powers up to 25 MW were demonstrated [3]. In addition, the overlap between the pump and the signal enables to reach small signal gain around 100 to 200.

ADJUSTABLE PARAMETERS

As an improved "bulk crystal" amplifier, the SCF technology keeps all the considerable advantages of usual bulk amplifiers, especially their ability to operate independently over a large range of repetition rate, pulse duration and seed power. The same SCF amplifier can be used, with no adjustment, to amplify a pulsed seed laser from a few kHz to several tens of MHz, or a seed laser from 10's of ns down to a few hundred of femtoseconds. Seed powers from a few hundred of mW up to tens of Watts were already successfully amplified [4][5].

SIMPLICITY

A typical single pass Yb:YAG SCF amplifier stage, in an industrial product, is composed of six optics, with only standard optical components and pump optics included. The laser beam is only subject to 3 reflections, and goes through the gain medium just once.
As a comparison, a typical thin disk or slab amplifier uses more than 10 or 20 optics, with a laser beam typically subject to 5 to 16 reflections and going through the gain medium more than 5 times.

Simplicity means reliability and ease of use. Amplifiers commercialized by Fibercryst have already accumulated more than 2 years of operation without maintenance or adjustments.

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Over 120 days of operation, without any tuning, a 20 watts sub-nanosecond laser system displayed less than 2 % RMS variation in output power.

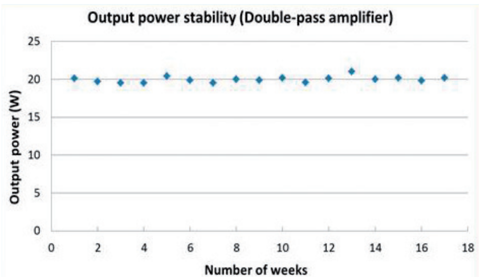

Figure 6: *Sub-nanosecond power output*

The SCF amplifiers are used with a variety of seeder lasers demonstrating the flexibility and the simplicity of the amplifier setup.

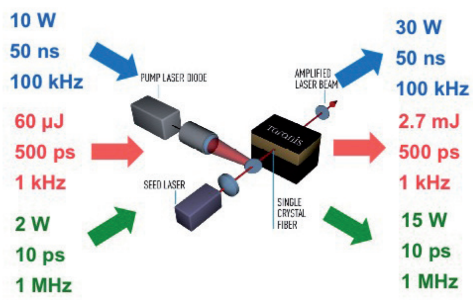

Figure 7: *Examples of SCF operation*

FROM AMPLIFIERS TO LASERS

The technical benefits of the Single Fiber Crystal technology have enabled Fibercryst to develop a line of high power short pulse lasers for industrial applications. These lasers are rugged, require no tweaking, and their performance can easily be tuned to best match the required set of parameters for a given process.

Using SCF amplifiers in cascade, selecting different seeders and tuning the repetition rate over a wide range, one can cover a very large set of performance.

For instance, Fibercryst now offers two families of products, one with picosecond outputs and one in the femtosecond regime, with various declinations depending on the required output power.

One family delivers less than 10 ps pulses with adjustable repetition rate ranging from 200 kHz to 2 MHz. Average power and peak power go up to 60 W and 10 MW respectively.

In the femtosecond domain also with adjustable repetition rate ranging from 100 kHz to 2 MHz. Average power and peak power go up to 25 W and 200 MW respectively.

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