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Review

Fused fiber components for parallel coherent fiber lasers

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Abstract. The concept of massively parallel coherent fiber lasers holds great promise to generate enormous laser peak power in order to produce highly energetic particle beams. Such technology is expected to provide a route to practical particle colliders or to proton generation for medical applications. Such concept is based on the phasing of thousands of fiber amplifiers each emitting mJ level pulses, in which optical fibers are key components. In this paper, we present important technological building blocks based on optical fibers, which could pave the way for efficient, compact and cost-effective components to address the technological challenges ahead.

1 Introduction

High energy lasers have experienced uninterrupted progress in their available intensity ever since the invention of the laser and more particularly since the advent of chirped pulse amplification. Several laser facilities around the world have exploited these unusual light intensity regimes to produce highly energetic particles, relativistic electrons and perform advanced nuclear physics experiments. The laser architectures implemented at such facilities typically operate with a few pulses per second (∼Hz) or less and produce extremely low average power. For such laser architectures to ever constitute practical solutions for particle accelerators and a proton source for radiation therapy, lasers need to achieve much higher average power with repetition rates at the kHz level, not to mention higher wallplug efficiency.

The Coherent Amplifying Network (CAN) concept relies on many fiber laser amplifiers, each amplifying a stretched laser pulse initially a few 10's of femtosecond in duration [1,2]. The many individual pulses are amplified and recombined to achieve ten's of Joules of energy, and compressed to achieve a few hundreds of femtoseconds. Fiber-based lasers have already demonstrated their many benefits for achieving high average power, enabling kilowatt levels with high efficiency. The CAN prototype is expected to integrate over a thousand amplifying fibers producing 10 TW peak power, over 10 kW (a factor 10 from the final CAN infrastructure) and better than 20% wall-plug efficiency.

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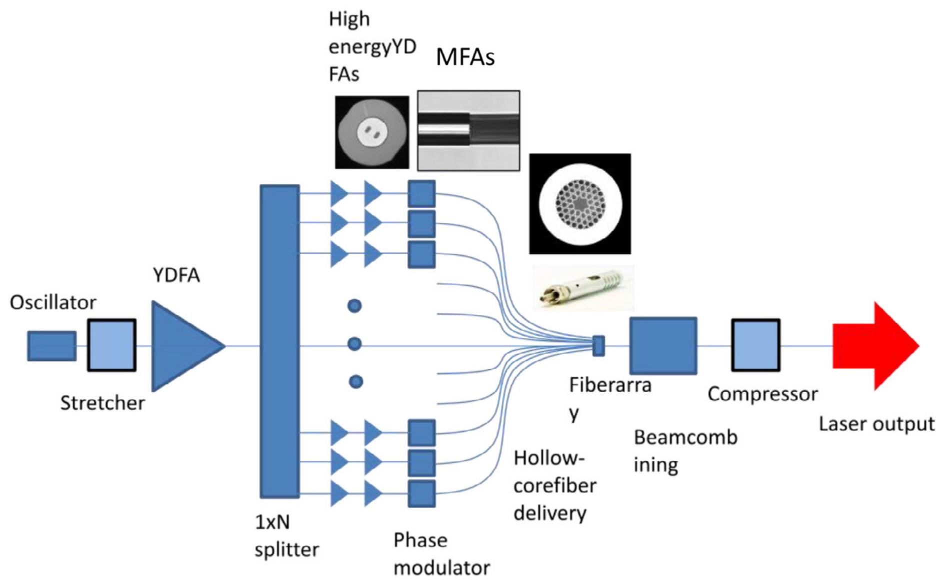

Fig. 1. Schematic of the massively parallel (N = 1000–10000) coherent fiber laser architecture. YDFA: Ytterbium-Doped Fiber Amplifiers; MFAs: Mode Field Adapters; the picture insets illustrate components developed by ALPHANOV.

Fiber components are therefore essential technological bricks in the considered laser architecture, from fiber laser amplifiers to $1 \times N$ fiber couplers that will be used to split the oscillator beam in thousands of sub-beamlines, from $N \times 1$ fiber combiners used to recombine those beamlines to mode-field adapters to interface each of the fiber components together (Fig. 1). For several years, ALPhANOV has developed advanced processes in fused fiber components fabrication and fiber preparation that should prove to be central for the CAN concept.

In this paper, we present progress in high power fused fiber components suitable as key building blocks for the CAN infrastructure. We review their technical performance, in particular in terms of efficiency in the overall laser architecture.

2 Fused fiber building blocks

The know-how developed by ALPhANOV revolves around four building blocks based on fused fiber technology:

i) Micro-structured fiber termination,
ii) Mode-field adapters,
iii) All-fiber monolithic micro-structured fiber amplifier for high energy amplification,
iv) Hollow core fiber delivery.

2.1 Micro-structured fiber termination

Micro-structured fibers, also known as photonic crystal fibers (PCF), have become ubiquitous in the field of photonics and high-power laser developments. These fibers exhibit unique light confinement properties that rely on the periodicity of their refractive index structure. The variety of possible architectures enable them to address

Table 1. Micro-structured fiber connector specifications.

Fiber type	**LMA, SC, NL, HC, Kagome**
Connector type	SMA, SMA905 (high power), FC, FC-APC
Sealing length	from 50 μm
Polishing angle	$0°$ up to $12° \pm 1°$
Max. input power	200 W per connector

applications in bio-imaging, metrology, sensors or industrial processes. The integration of such micro-structures fibers in photonic systems relies on the capability to interface and connect their ends that can often have delicate geometries, making them difficult to package. ALPhANOV developed a process to interface micro-structured fibers, photonic crystal fibers and hollow-core fibers whose ends are hermetically sealed and then polished with a controlled angle. The connector includes a mode-stripper that insures that power coupled outside the fiber core or cladding does not reach the polymer jacket. For PCF and air clad fibers, fiber ends are hermetically sealed with a sealed length as short as possible to ensure excellent integrity of the fiber parameters (polarization, beam quality, etc.).

This know-how makes it possible to produce micro-structured fibers with integrated end-caps that are able to withstand high average power, thanks to the mode-stripper design. They are compatible with polarization maintaining fibers (alignment key) and can be angle-polished with $0.5°$ precision. Moreover, the process allows splices to be performed with extremely low loss, in order to maintain high overall efficiency. The process can be scaled up to larger fiber diameter, such as Large Mode Area fibers or even rod-type fiber, with millimeter-sized end-caps to accommodate high power densities. Table 1 summarized some of the measured technical specification that these connectors can achieve.

2.2 Mode-field adapters

In recent years, fiber laser systems have been employed in a wide range of demanding applications. This led to the widespread use of novel large mode area (LMA) fibers and other special fiber technologies. Mode field adapters (MFA) are becoming key components to optimize fiber system efficiency in advanced high power fiber lasers. Indeed, MFA's enable mode matching between two different fibers, hence optimizing transmission from one fiber to another. A CAN laser will involve a large number of components and fibers where every loss will impact significantly the overall system wall-plug efficiency; MFA will not only improve system efficiency but also improve stability since the current technology is based on fused fibers. Thanks to advanced fiber processing developed at ALPhANOV, it is now possible to produce MFAs capable of matching extremely different mode field diameters with very low loss. For instance, it is possible to adapt mode from standard single-mode fiber with a mode field diameter (MFD) of about 6 μm up to MFD exceeding 60 μm in a fully fiber fused configuration. The associated loss can be reduced to less than 1.5 dB on the signal fiber and to less than 0.5 dB on the pump fibers.

2.3 All-fiber monolithic micro-structured fiber amplifier for high energy amplification

The combined know-how of designing high-power fiber combiners and mode-field adapters to match a standard single-mode fiber to a micro-structured fiber led

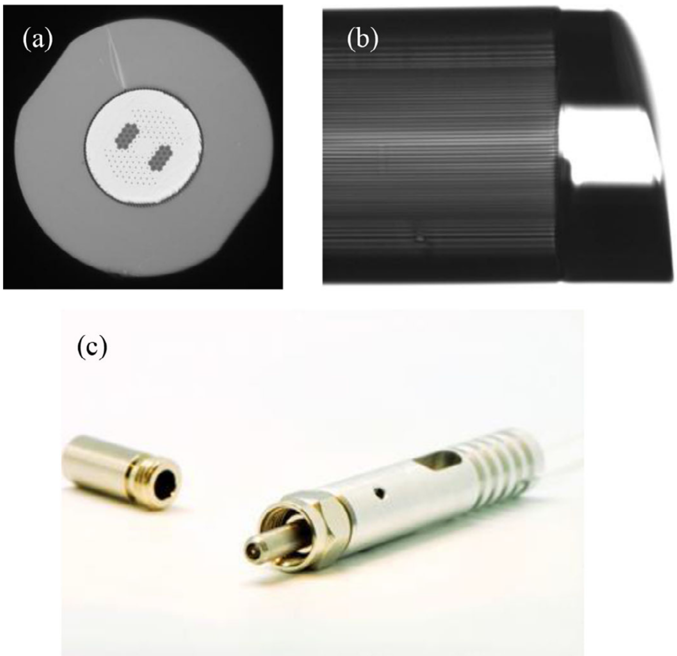

Fig. 2. End-caps on Yb-doped PCF fiber (NKT DC-200/40-PZ-Yb). (a) Front and (b) side view. (c)Micro-structured fiber connectors.

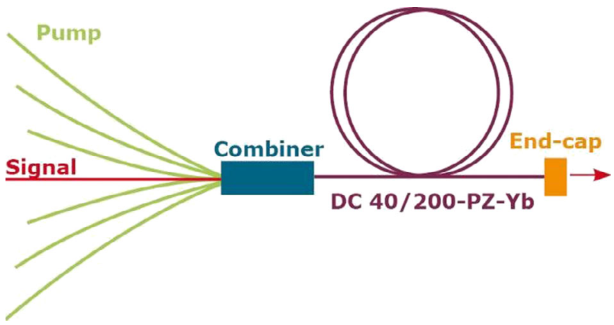

Fig. 3. Principle of the monolithic micro-structured fiber amplifier.

ALPhANOV to design a special pump combiner for active micro-structured fiber [3]. This combiner consists in N pump fibers and a signal fiber at the input side, and a single output fiber delivering the amplified signal (Fig. 3). This unique component enables to combine pump and signal in a PCF fiber in a fully monolithic architecture for a fiber amplifier based on active micro-structured fibers. With a length of less than 2 m and a MFD of about 30 μm, this amplifier ensures high quality pulse amplification with much lower impact on the B-integral than conventional large mode area fibers. In addition, this highly advanced fiber amplifier offers robustness, high efficiency and potential compactness, thanks to a fully fused large core fiber amplifier, ideally suited for high energy short pulse amplification. Moreover, this amplifier relies on fused fiber technology which is easily scalable and suitable for mass-production at low cost.

Such a laser amplifier based on an Yb-doped active fiber in a $2 + 1 \times 1$ configuration was developed by ALPhANOV using the DC-200/40-PZ-Yb fiber from

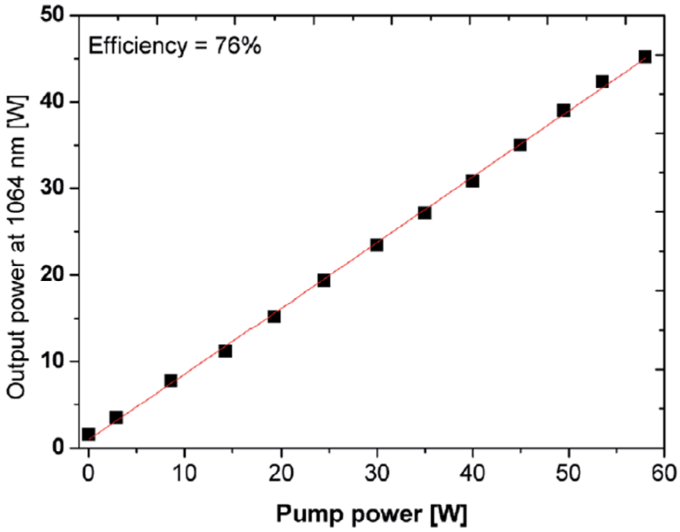

Fig. 4. Efficiency curve of the monolithic micro-structured fiber amplifier.

Table 2. Technical specifications of the micro-structured fiber amplifier.

Type	$\mathbf{2 + 1 \times 1}$
Input power	2W
Input pulse duration	10 psec
Input rep. rate	100 MHz
Pump power	50 W per port
Output power	45 W
Efficiency	76%

NKT Photonics. Each pump port can accommodate over 50 W of pump power. The prototype was pumped at 60 W total power at 976 nm. The signal was injected in a 15 μm diameter input fiber at 2 W average power, 10 psec pulse duration and 100 MHz repetition rate. The output power reached over 45 W at 1064 nm, demonstrating over 75% efficiency (Fig. 4).

Table 2 lists the technical specification achievable by the monolithic micro-structured fiber amplifier integrating the DC-200/40-PZ-Yb fiber.

2.4 Hollow core fiber delivery

The CAN laser architecture also relies on a large number of high energy beams exiting fiber amplifiers to be coherently combined in an array of high-energy beams. Fiber optics can be profitably used to deliver this beam in a bundle with a compact cross-section. However, standard optical fibers consisting of a silica core exhibit nonlinear properties that are detrimental to the laser beam, especially at such high power densities. Hollow core fibers, on the other hand, allow reduced nonlinearities thanks to a very low overlap between the high energy propagating beam and silica. In newly developed hypocycloid Kagome fiber, this overlap was estimated to be as low as 0.01%. This led to the demonstration of fiber delivery of high energy ultrashort pulses [4] and record transmission of 1 mJ femtosecond pulses [5].

Kagome fibers are currently used in laboratory environments. Introducing this technology into the CAN laser architecture requires the development of solutions for industrial integration, which ALPhANOV can supply.

Fig. 5. Concept of "stackable" fiber amplifiers based on the monolithic $\mathrm{N} + 1 \times 1$ combiner on active micro-structured fiber. (For illustration purposes, the number of amplifiers was chosen to be equal to 8.)

3 Conclusions on potential benefits for the CAN infrastructure

The main benefits of fused fiber components for the CAN architecture rely in the high efficiency and high scalability that are intrinsic to this technology. Current prototypes presented in this paper have combination ratios between 2 and 7, but there is no inherent limitation to this technology and combination ratios of over 1000 can be envisaged. For instance, one could imagine stacking several, say 8, of the monolithic $\mathrm{N} + 1 \times 1$ laser amplifiers together. Thermal management being one of the practical limitations that should be taken into account, stacking 8 combiners remains reasonable as common heat sinks can be used. If we assume that each of these amplifiers are $6 + 1 \times 1$ combiners, with a total of 48 pump fibers and 8 signal at the input and that the 8 output fibers are recombined together, that amount to 360 W of output power. With 30 of such stacks depicted in Fig. 5, the 10 kW of average power targeted by the CAN prototype can be reached.

It is difficult to extrapolate precise wall plug efficiency as this depends on many elements of the system but the ultralow interface loss typically achievable on fused fiber components, the high efficiency of the monolithic fiber amplifier presented in this paper and the high robustness of fibered architectures make them strong candidates for potential integrations in the CAN infrastructure.

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