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HIGH POWER PULSED SOURCES BASED ON FIBER AMPLIFIERS

Guillaume Canat(1), Yves Jaouen(2), Jean-Claude Mollier(1), Jean-Pierre Bouzinac(1), Jean-Pierre Cariou (1)

(1) ONERA – DOTA, 2, avenue Edouard Belin 31055 Toulouse, France, guillaume.canat@onecert.fr
(2) GET Telecom Paris - CNRS UMR4151, 46 rue Barrault, 75634 Paris , France, jaouen@com.enst.fr

ABSTRACT

Cladding-pumped rare-earth-doped fiber laser technologies are currently among the best sources for high power applications. Theses extremely compact and robust sources appoint them as good candidate for aeronautical and space applications.
The double-clad (DC) fiber converts the poor beam-quality of high-power large-area pump diodes from the 1st cladding to laser light at another wavelength guided in an active single-mode core. High-power coherent MOPA (Master Oscillator Power Amplifier) sources (several 10W CW or several 100W in pulsed regime) will soon be achieved. Unfortunately it also brings nonlinear effects which quickly impairs output signal distortions. Stimulated Brillouin scattering (SBS) and optical parametric amplification (OPA) have been shown to be strong limitations.
Based on amplifier modeling and experiments we discuss the performances of these sources.

1 INTRODUCTION

This section sums up the main characteristics of fiber sources and their applications. Section 2 describes the major steps which allowed fiber sources to grow in optical power. Section 3 describes the main limitations to build high power pulsed sources. Section 4 gives an overview of the project of the ONERA/DOTA.

Lasers and amplifiers built with rare earth doped fibers (REDF) gather several advantages (table 1) over other sources [1] :

- *High efficiency*

The fiber laser efficiency can be close to the theoretical quantum efficiency of the laser transition. The recent availability of pump diode bars with high brightness allows to reach high average powers. High power continuous and pulsed laser have thus been demonstrated: up to 7 kW continuous [1, 2] at 1 µm ; up to 103 W continuous at 1,56 µm in an Erbium-Ytterbium fiber strongly multimode [3]. The best narrow linewidth currently reaches 15 W continuous [4].

- *Very efficient heat dissipation*

Fibers take advantage of a much higher ratio volume / cross section than rods and disks frequently used in solid states laser. The heat generated by the pump absorption is thus easily dissipated. Fiber lasers are immune against thermo-optical problems.

- *Excellent beam quality*

Beam quality factors M^2 for low order multimode fibers below 2 are usually reached. $M^2 < 1.2$ has been demonstrated.

- *Large gain spectrum*

The large width of the rare earth gain curve allows to use broad bands of wavelength.

- *Compact and robust source*

These laser sources show (typically 100 000 hours or higher), compactness and robustness in operation (no active cooling required), few maintaining operation.

Pulsed systems now reach several millijoules for Ytterbium doped fiber systems [5] and several hundred of microjoules with Erbium-Ytterbium doped fiber systems [6].

Table 1. Comparison between several laser types.

Type	CO_2	Nd:YAG lamp-pumped	Nd:YAG diode-pumped	High Power LD bars	Yb Fiber Laser
Wavelength (µm)	10.6	1.06	1.06	0.8-0.94	1.0 –1.08
Plug Efficiency (%)	5-10	1-3	10-12	30-50	> 40
Power density (W / cm2)	$10^{6..8}$	$10^{5..7}$	$10^{6..9}$	$10^{3..5}$	$10^{8..10}$
MTBF (hours)	1000-2000	200	5000-10000	5000-1000	>10000
Fiber coupling	No	Yes	Yes	Yes	Yes !
Beam parameter (mm x mrad)	12	25-45	12	100-1000	1-8
Compacity		+	++	+++	++

Applications

Fiber sources could potentially be used in many fields:

- Ranging
- Parametric optical amplifiers pumping for non-linear frequency conversion
- Spectroscopy [7]
- Metrology (distance measurement, gravimetry with cold atoms)
- LIDAR application using coherent or direct detection [8]

- Space communications

The main advantages of fiber sources in these applications are wavelength versatility, high brightness, narrow linewidth and low RIN. The rare-earth incorporated into the fiber allows to address many spectral windows: Ytterbium (980-1100nm range), Erbium (1520-1650nm), Thulium (1750-2100nm range). With a typical numerical aperture NA = 0.1, a mode field diameter of 10 um, a fiber laser brightness is still 3 times larger than diode pumped YAG laser reaching 2 GW/cm^2/sr. This brightness directly favors fiber sources for material processing or OPO pumping.

Some applications such as LIDAR or coherent communications required narrow linewidth sources. Low power DFB erbium doped fiber laser can be used as injectors for MOPA architectures. Today these lasers can reach 2kHz to 15kHz linewidth [9][10]. Their RIN is characterized by a peak at a relaxation frequency near 1MHz. It then quickly decreases below –14dB/Hz after a few MHz. The ONERA is currently working on wavelength locking on a Rubidium line of an Erbium/Ytterbium fiber laser. This laser (built by Koheras/IDIL) exhibit a very low RIN above 10MHz (<160dB/Hz, measurement done by ENSSAT in Lannion - France) (Fig. 1)

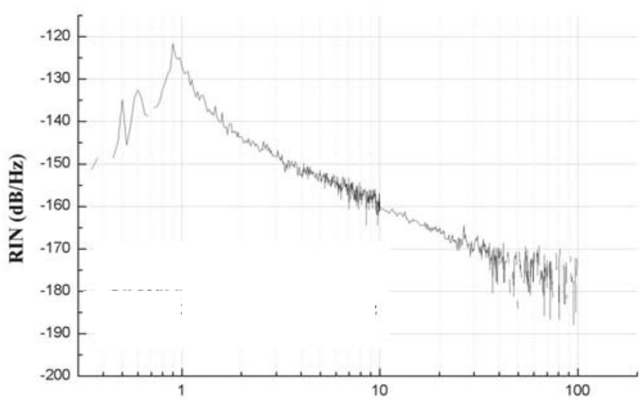

Fig. 1 RIN spectrum of the Erbium-Ytterbium fiber laser for wavelength locking at the ONERA.

In cooperation with Thales/Avionics, the ONERA/DOTA built a 1.5 µm LIDAR demonstrator. This MOPA continuous coherent fiber LIDAR is built around a 30 dBm Keopsys amplifier and is designed for use on board a helicopter. Its good vibrations handling capacity illustrates the robustness of fiber sources.

2 THE ROUTE TO POWER SCALING

We now focus on Erbium-Ytterbium Doped Fiber (EYDF). The output power scaling in EYDF is limited by the amount of pump power which can be coupled into the fiber.

A maximum of 700 mW output power in a single-mode fiber for a 980 nm pump laser diode has been presented [11]. However, the typical output powers of fiber-pigtailed pump laser sources with high reliability are limited in the order 250-350 mW by intrinsic materials properties of the laser diodes themselves (e.g., facet damage). The corresponding available output power in double pumping configuration (co- and counter-propagating with respect to the signal) is 21-23 dBm depending on the pump powers and EDFA architecture.

A major step was done with the use of double-clad (DC) fiber which allow to use multimode broad stripe pumps. High power broadband area laser diodes with > 4 W output power are commercially available [12]. Pump lasers with up to 10 W in a 100µm 0.22 NA fiber should be soon released [13]. The DC fibers are composed by two steps: a large multimode guiding region for the pump light propagation and a single-mode doped core for the signal. The pump light is coupled from the multimode 1st cladding into the active monomode core over the entire DC fiber length. The DC fiber acts as a beam converter from the poor-quality output beam from high power large-area laser to a light laser at another wavelength guided by single-mode core. Output powers using a DC geometry now reach records. Using a Nd/Yb codoped fiber laser operating in CW mode, a group of the Friedrich-Schiller Universität produced up to 500 W at 1100 nm with a slope efficiency of 72% [14]. The group of Southampton university produced 103 W at 1560 nm [3].

2.1 1st cladding geometries

Pump light is only absorbed when the rays occasionally cross the doped single-mode core. Due to the small area ratio A_{core}/A_{clad}, the coupling of the pump light from the to the doped core is relatively weak. The pump absorption is strongly determined by the 1st-cladding geometry.

The pump cladding absorption can be expressed as:

$$\alpha_{clad} = K \frac{A_{core}}{A_{clad}} \alpha_{core} \qquad (1)$$

where α_{core} and α_{clad} are the absorption in the core and the cladding respectively and K < 1. If the pump field was uniformly distributed across the first cladding, we would have K = 1. Due to the propagation of helical fiber modes only a fraction of the pump light can be absorbed in a circular cladding DC fiber and K < 1 [15]. Special cladding geometries were studied to offer both high K factor and good mechanical properties [16]. The usual cladding geometries proposed by specialty fibers manufacturers are: flower (OFS), hexagonal (INO, …), rectangular (Polaroid, Highwave, …), D-shaped. Theses types of DC fibers can be spliced using automatic splicers. At very high pump power, special geometries including several layers improve the thermal behavior.

2.2 Pump injection solutions

Different techniques for DC pump injection have been proposed in the literature. We describe here the more reliable solutions for high power amplifiers design. Essentially, three clad pump techniques have are used in commercially available systems:

- MultiMode (MM) coupler [17, 18]

MM-core fiber pigtailed pump modules with output power up to 2.5 W are commercially available. The light is then guides into the inner cladding using MM coupler. Special tapered fiber bundles have been designed to combine up to 6 MM fibers which can be spliced directly to the DC fiber. Up to 15 W can thus be coupled.

- Proximity coupling [19]:

In the fiber assembly there are two or more optical fibers surrounded by a low-index coating. One of the fibers is all-silica core-less whereas the other fiber has a doped core. The fibers are in optical contact and can be processed independently when the external coating is stripped off. Pump light from a MM fiber pigtailed diode is launched into the undoped fiber and propagates freely through both fibers. SPI optics offers this kind of fiber known as GT-Wave fiber.

- V-groove-side pumping (VSP) [20]:

The pump diode beam is captured by a micro-lens and re-focused on the facet of a V-groove fabricated in the side-wall of the DC fiber. The incident pump light is coupled into the 1st-cladding after underground total internal reflection at 45° glass-air interface of one of the V-groove facet. Diode to inner cladding coupling efficiency up to 90% has been measured.

2.3 Erbium/Ytterbium codoping

The Erbium ions concentration in the core is limited by clustering effect [21]. The maximum pump absorption cross-section is about $2x10^{-25}$ ions.m^{-3}. Therefore the effective pump absorption of a pure Erbium doped fiber would be pretty low.

The Ytterbium ions concentration can be several tens times higher. Moreover the 977 nm pump peak absorption is twice larger than with 975 nm Erbium. The proximity between the transitions $2F_{7/2}$ to $2F_{5/2}$ and $4I_{15/2}$ to $4I_{11/2}$ allows resonant coupling between Ytterbium and Erbium ions. Thus pump power can be absorbed by Ytterbium with high rate an transferred to Erbium to benefit from high absorption and 1,55µm band.

Power scaling of lasers and amplifiers at 1,55 µm thus quickly directed towards Erbium-Ytterbium fibers (Fig. 2). It should be however noted that these fibers are more challenging to make: not only have Erbium and Ytterbium concentration to be tuned to get a good transfer rate, but Aluminum and phosphorous have to be introduced too. Aluminum is required to increase rare earth solubility and avoid clustering ; phosphorous is added to reduce the Erbium $4I_{11/2}$ excited level lifetime and thus reduce the backtransfert from Erbium to Ytterbium.

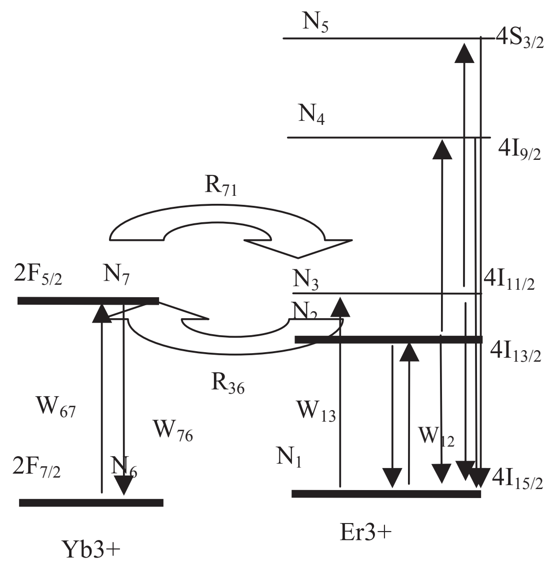

Fig. 2. The Erbium-Ytterbium energy diagram

The basic equations for the modeling of Erbium-Ytterbium system can be found in several papers [22, 23].

3 POWER SCALING LIMITATIONS

3.1 Maximum extractable energy

If continuous wave amplifiers performances are now well-known and modeling, amplifiers in pulsed regime have a more complex behavior.

Aside numerical models, we use a semi-analytical model which provide great insight in the physics of pulsed amplifiers. We adopt the following hypothesis:

- The transfer rate Ytterbium -> Erbium is slow compared to the non-radiative decay of $4I_{11/2}$. level. This level is thus empty.
- Background loss and pairing are neglected (no upconversion or pairing …)
- The transverse dependence is reduced by the overlap integral approximation.
- SBS and SRS nonlinear effects are neglected.

We the define the saturation energy at the signal wavelength by :

$$E^{sat} = \frac{h\upsilon\ A}{(\sigma_a + \sigma_e)\Gamma} \qquad (2)$$

Γ is the overlap factor at the signal wavelength between the signal mode and the doped zone, $h\nu$ is the photon energy, σ^e and σ^a are the emission and absorption cross-section at the signal wavelength and A is the area of the doped zone. For a usual telecom fiber, $E_{sat}<5\ \mu J$.

We then assume that pulses whose peak power is high compared to the saturation power enter the amplifier. The gain can then be analytically computed during the pulse [23]:

$$G(t) = \frac{G_o}{G_o + (1 - G_o)\exp - \dfrac{E_{in}(t)}{E^{sat}}} \qquad (3)$$

where G_o is the amplifier gain just before the pulse arrival, corresponding at t = 0, $E_{in}(t)$ is the energy which entered the amplifier. This expression is called the Franz-Novdik relation for an amplifier [24].

It can then be shown that the output energy per pulse does not depend on the pulse shape:

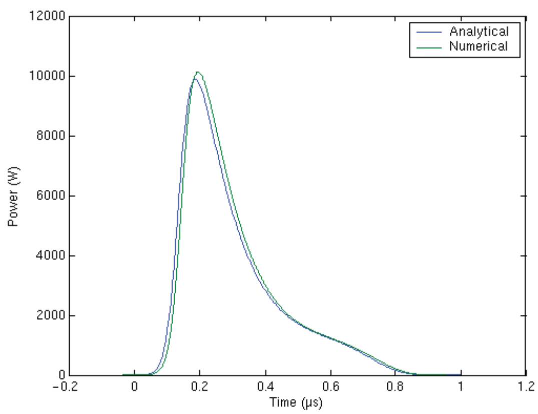

Fig. 3. Comparison between (3) and a numerical model for pulse amplification at 1 kHz repetition rate.

—— (4)

When $E_{in}>>E_{sat}$, The output energy can be simply expressed as:

$$E_{out} = E_{in} + E_{sat}\ln(G_o) \qquad (5)$$

G_o is the only parameter to estimate. At low pulse repetition rate or very high repetition rate, it can be computed using a continuous wave model assuming that the input power is the average input power in the real situation. Figure 3 shows the excellent agreement at low pulse rate between this model and a full numerical one.

Using (4), we estimated the extractable energy for several fibers (Fig. 4). As the saturation energy scales with the doped area, we can see that large pulse energy requires fiber with large doped core.

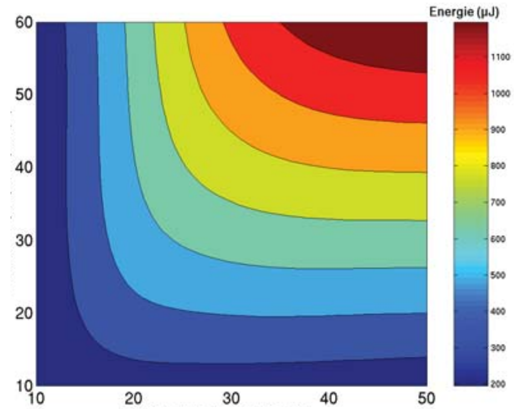

Fig. 4. Extracted energy by 100 µJ from a 3m fiber amplifier.

Solid state lasers can be seen as a limit of this scaling process.

3.2 Non linear effects

The efficiency of fiber lasers and amplifiers comes from the tight confinement of the optical mode into the core. However, the resulting small mode field diameter is also the source of limitations due to non-linear effects.

Non-linear effects arise from the change in the silica properties by high intensities. Their threshold thus scales with the ratio L_{eff}/A_{eff} where L_{eff} is an effective length and A_{eff} is the effective area of the fundamental guided mode ($A_{eff} = \pi\omega^2$ in gaussian field approximation where ω is the mode field diameter)

For narrow linewidth sources, the first non-linear effect to appear is the Stimulated Brillouin Scattering (SBS) [25].

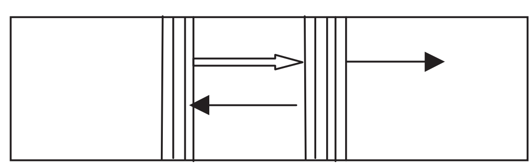

Fig. 5. Stimulated Brillouin Scattering principle.

SBS originates from the interaction between the signal and acoustic waves in the fiber (Fig. 5). A small fraction of the pump is scattered in a counterpropagating beam called the Stokes wave. When the signal reaches a threshold, the process becomes stimulated and the Stokes wave is amplified until complete depletion of the signal. The Stokes wave is downshifted by ~ 11 GHz.

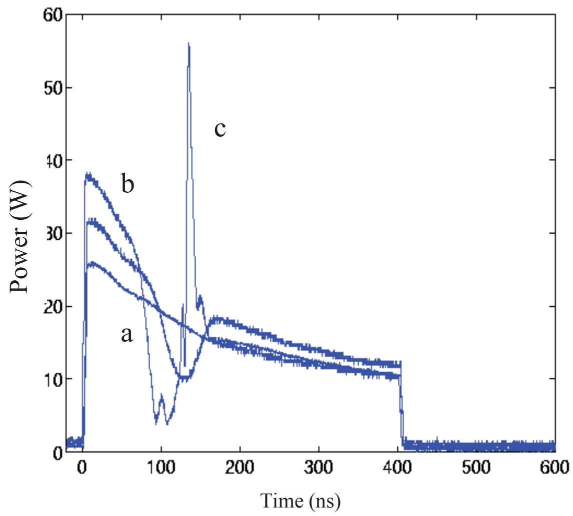

Fig. 6. Amplification of rectangular pulses by a 1 W amplifier for three increasing input peak power (a) below threshold. (b) above threshold. (c) above the 2nd order threshold.

The Stokes wave can be powerful enough to be scattered into a second order. The total spectrum will thus be spread over several GHz. In an amplifier, every scattering will act as a (distributed) mirror and every Stokes order will be amplified up to be several times more powerful than the signal itself. It can be strong enough to destroy optical components such as isolators. In the time domain, the signal power drops periodically (Fig. 6). The period is the round-trip time of light in the fiber. A numerical model is developed at the ONERA/DOTA including SBS and gain dynamic to get greater insight into the amplifier behavior [26].

A rule of thumb can be derived to estimate the SBS threshold using the Smith relation [27]:

$$\frac{g_B L_{eff} P_{seuil}}{A_{eff}} = \chi \qquad (6)$$

where $g_B \approx 3\mathrm{x}10^{-11}$ $m^{-1}.W^{-1}$ is the Brillouin gain in silica fibers, A_{eff} is the fiber effective area and P_{th} is the threshold power at the output of the amplifier, χ is a unitless number which changes slowly with the amplifier gain, length and effective area. $L_{eff}=L_{physical}/\ln(G)$ with G the amplifier gain and $L_{physical}$ its length.

This relation was derived for passive fibers as long as several kilometers. In that case, χ is closed to 21. For active amplifiers (6) holds with a χ slightly different which can be numerically estimated [27].

Using this rule, it appears that double-clad fibers should have a large core and a small 1st-cladding to core ratio. It would indeed allow to reduce A_{eff} and L_{eff} as the pump would be absorbed on a shorter length. The reduction of the 1st-cladding is only possible now with the availability of high brightness pump diodes which can be coupled into 100 µm fibers. A threshold several dB higher is thus forecast.
The Kerr effect is another relevant effect. The nonlinear Kerr parameter of a Er^{3+}/Yb^{3+} co-doped fiber has been measured using the FWM method [28]. The FWM products are generated by a two co-propagated signal pumps with co-linear polarization arrangement. These two pumps can be degenerated. The Kerr non-linear coefficient γ_{ErYb} of the Er^{3+}/Yb^{3+} co-doped fiber is evaluated ~ 15 $W^{-1}km^{-1}$ which is somewhat higher than in undoped fiber. Kerr effect in fibers is responsible for FWM, SPM and XPM which would be relevant in a context of spatial optical communications [24]. In the context of high power pulse generation, FWM is the most relevant non-linear effect as it is responsible for optical parametric amplification [24]. Using a simple 1 W amplifier with a mode area of 50 μm^2, we observed OPA which impairs the spectral purity of the signal below 1 kW.

As with SBS, an increase in the core diameter and a decrease in the fiber length should help to enhance the SBS threshold by several decibels .

4 BUILDING A NARROW LINE-WIDTH HIGH-ENERGY PULSE SOURCE

The ONERA/DOTA is currently working on a fiber source at 1,55µm for coherent detection LIDAR applications. This wavelength has a high scattering efficiency by aerosols and falls in the eye-safe window. Our aim is building of a source delivering 1mJ over 400ns with a narrow linewidth below 1MHz.

Our source is thus based on a 3 stages MOPA architecture. SBS will clearly be an issue. To store enough energy into the final stage and rise the SBS threshold we develop DC fibers whose core diameter would be larger than 30µm. With such a large diameter, the fiber not support not only one mode. As the beam quality is an issue in any application, specific solution have to be found.

The number of modes increases with the normalized frequency V = k.a.NA. The numerical aperture cannot go below about 0.06 as the bend losses would become unacceptable. Moreover, making fibers with such a low NA is uneasy as the core doping by rare earth and phosphorous gives an index step of several

10^{-3}. Several solutions can be proposed to circumvent the difficulty:

- *Low NA fibers*

Koplow, Kliner, Goldberg have proposed to coil the fiber on a drum in order to introduce bend loss [29]. As the loss depends exponentially on the bending radius, a good choice of the coil radius can introduce low losses for the fundamental mode and large losses for the higher order modes. If the NA is low enough, the bending radius is large enough to limit abnormal aging.

- *Photonic crystals fibers [30]*

With photonic crystals structures based on total internal reflection, monomode fibers with very large mode area can be theoretically designed. An Yb^{3+} fiber laser with an effective area of 100µm^2 has been demonstrated [31]. It should however be noticed that this kind of doped structures is very complex to make. Some 1D photonic crystals based on the Forbidden Photonic Gap, the so called Bragg fibers [32], could also theoretically be used to build large mode lasers.

- *Large mode area (LMA) fibers [33]*

A LMA fiber, proposed by Southampton University, consists of a core step surrounded by several rings. This structure is claimed to help to reduce the bend losses.

These solutions have been demonstrated for large core Ytterbium doped fibers. We work on manufacturing low NA Erbium-Ytterbium doped fiber. The phosphorous doping which is compulsory for these fibers is a source of difficulties during the preform preparation.

This fiber (DC) will be used to build the last stage of a three stage amplifier (Fig. 7). The injector (In) is a 30 mW DFB laser diode whose output is externally modulated by an acousto-optic modulator. It allows to reach a high extinction ratio. The first stage (A1) amplifies the 400ns pulses to about 10 W peak power. Second stage (A2) should amplify them to 250 W and last stage to about 2.5 kW to reach 1 mJ.

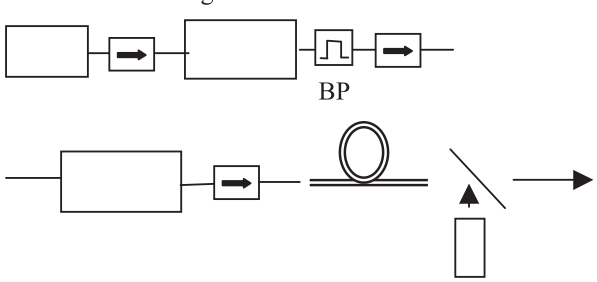

Fig. 7 Description of our fiber source. (In: DFB injector ; A1: first stage ; A2: second stage ; DC: double clad large core fiber ; M: dichroic miror ; DL: 60 W pump diode)

In order to increase the saturation energy, each stage use a larger fiber. Besides, it increases the SBS threshold. Using a small ratio cladding diameter / core diameter for the last stage allows to absorb the pump on a shortest fiber. This length reduction provides additional gain on the SBS threshold (6).

The counterpropagating pumping configuration reduces the effective interaction length as the high power zone is limited to the end of the fiber.

With thus hope to reach 1kW peak power with a narrow linewidth injector without SBS effect.

5 CONCLUSION

The main advantages of fiber sources are wavelength versatility, high brightness, narrow linewidth and low RIN. Fiber is a robust way to distribute the laser beam.

Until recently, the high power were limited by low energy storage and non linear effects. A special effort on fiber design aided by high power pump diodes progress opens now new perspectives.

Using our modeling and testing the ONERA/DOTA builds a demonstration for a 1mJ narrow linewidth pulsed source using Erbium-Ytterbium doped fibers.

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