Sub 500 fs high power quasimonolithic FCPA laser using an all-solid step-index flexible PM VLMA Yb-doped fiber amplifier

Tristan Guezennec[a], Laurent Provino[a], Eric Lallier[b], Olivier Le Goffic[a], David Landais[a], Achille Monteville[a], Thierry Taunay[a,*], and Adil Haboucha[a]

[a]Photonics Bretagne, 4 rue Louis de Broglie, Lannion, France
[b]Thalès R&T, 1 Av. Augustin Fresnel, Palaiseau, France
[*]*currently at* Lumibird, 2 rue Paul Sabatier, Lannion, France

ABSTRACT

We report on the design of a quasi-monolithic fiber chirped pulse amplification (FCPA) system operating at 1040 nm. Chirped-pulse amplification has been achieved using an all-solid step-index PM VLMA Yb-doped fiber, designed and drawn at Photonics Bretagne. The amplifier is integrated to the system through an internally developed mode field adapter (MFA), and bended with a 14 cm diameter, giving a truly single-mode behavior. 540 fs pulses are obtained without any fiber length optimization. An average power of 50 W has been achieved at the fundamental repetition rate of the laser, but also energies up to 41 µJ per pulse at lower repetition rate, pump power limited. The pulses are stretched using a thermally–controlled tunable chirped fibered Bragg grating (CFBG), allowing fine dispersion tuning, and compressed using a chirped volume Bragg grating (CVBG).

Keywords: Ultrafast fiber laser, VLMA fiber, Yb-doped fiber, High-power laser

1. INTRODUCTION

Chirped pulse amplification has enabled the development of high power femtosecond lasers. Its usage with bulk amplifiers leads to pulses energies up to the joule level. However, their design makes them difficult to use outside the laboratory. The development of femtosecond fiber lasers has made easier their use in-situ, but their energy levels remain low. Microjoule-level laser systems based on a single-stage booster were demonstrated using rod-type photonic crystal fiber (PCF) amplifiers and bulk optics for energies up to 50 µJ at 500 kHz.[1] Developement of Yb-doped PCF and tapers allowed monolithic systems up to 100 µJ at low repetition rates, typically 1 kHz in a truly monolithic system,[2] but these amplifiers are still difficult to implement.

Here we present a quasi-monolithic FCPA system producing 41 µJ pulses using an all-solid step-index PM VLMA Yb-doped fiber amplifier (VLMA-40-220-PM-YB, product line Perfos®). Further optimizations should allow higher pulses energies, as well as shortest pulse durations. Step-index design of the fiber amplifier leads to an easy integration on monolithic systems, improving reliability especially for outside of the lab applications, or industrial use. Use of Bragg gratings for pulse stretching and compression allows greater compactness, since they exhibits high dispersion in a small volume (typ. few cm^3). They are also much easier to align than bulk gratings based stretchers/compressors.

2. MAIN YB-DOPED FIBER AMPLIFIER

2.1 Design and fabrication

The VLMA-40-220-PM-YB fiber consists of an all-solid step-index fiber, composed with a 38 µm core diameter, and cladding dimensions equal to 226 µm on the major axis and 180 µm on the minor axis, surrounded by a low-index polymer. Two opposites flat sides allow a preferential bendind direction for a better single-mode operation, and minimize the fundamental mode losses. The core preform has been manufactured using a chemical

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Further author information: (Send correspondence to T. Guezennec)
T. Guezennec: E-mail: tguezennec@photonics-bretagne.com

vapor deposition method and chelate precursors. A SEM image of the fabricated fiber, and the longitudinal refractive index profile of the Yb-doped preform are shown in Fig. 1. Taking into account cladding index fiber draw tension induced change, we estimated the fiber NA of the VLMA-40-220-PM-YB to be on the order of 0.045±0.005. Also, we can observe an excellent uniformity of the refractive index profile along the preform.

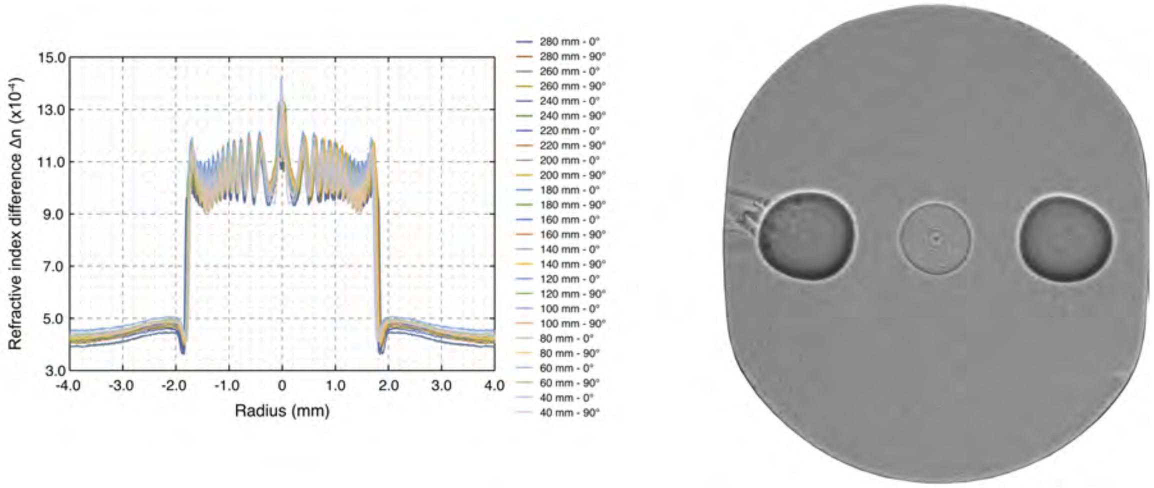

Figure 1. Left: Longitudinal refractive index profile of a low NA Yb-doped preform; Right: SEM image of the fabricated fiber.

Geometrical parameters optimization have been performed using numerical simulations based on finite element method (FEM), in order to evaluate the modal performances of the fiber. The results of the FEM simulations are depicted in Fig. 2. It can be shown that the fiber exhibits higher-order modes (HOMs) losses greater than 10 dB.m^{-1} when bended with a diameter less than 18 cm, regardless of the bending direction.
With a 15 cm diameter, the fundamental mode losses are around 1 dB.m^{-1}, so the fiber must be use with a bend diameter of 15 cm to 18 cm for a truly single-mode operation, allowing greater compactness. As it can be seen, the fiber exhibits greater fundamental mode losses when its bended in a perpendicular direction to the stress rods axis. So the opposites flat sides act as a bending orientation assisting mechanism.

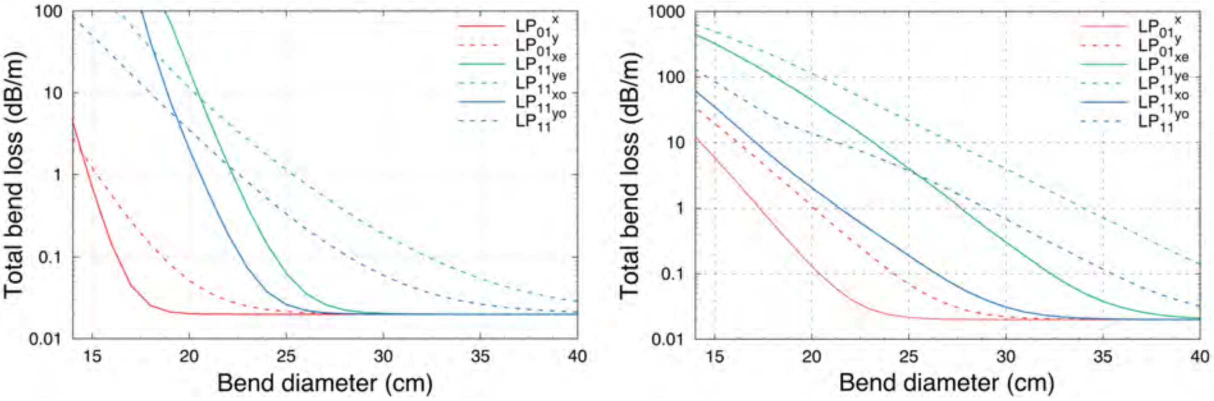

Figure 2. Simulated losses of the LP$_{01}$ and LP$_{11}$ modes of the fiber with respect to the bend diameter. Left: Bend direction along the stress rods axis. Right: Bend direction perpendicular to the stress rods axis.

2.2 Fiber performances

In order to mitigate photodarkening effects, a glass matrix with Al_2O_3/P_2O_5 codoping was used.[3] The photodarkening effects were evaluated with a monofrequency CW laser operating at 58 W. A 2 % average power decrease was observed for a 60 h endurance test, confirming low photodarkening operation.

At 976 nm wavelength, the core preform absorption was measured at 280 dB.m^{-1}, giving an estimated cladding absorption of 8.5 dB.m^{-1}. On fiber, the cladding absorption was measured at 915 nm and 976 nm wavelengths by measuring the small signal transmission spectrum, for different fiber lengths between 0.3 m and 5 m. The absorption values measured are respectively equal to 2.9 dB.m^{-1} and 8.5 dB.m^{-1} for 915 nm and 976 nm. A typical small signal transmission spectrum is shown in Fig. 3.

In order to validate the fiber design, the fiber was implemented in a MOPA system, operating at 1030 nm, with a repetition rate of 40 MHz, a pulse duration of 250 ps and an average power of 5 W. For these experiments, the 2.5 m VLMA-40-220-PM-YB fiber was coiled on bending diameter from 15 cm and 30 cm. The results are depicted on Fig. 3. Amplification up to 215 W was achieved with a 85 % efficiency and a polarization extinction ratio (PER) of 17 dB. We can observe that for diameters greater than or equal to 20 cm, the fiber presents excellent output beam quality ($M^2 < 1.2$). This behavior was attributed by the control of the injection in the core fiber using a MFA allowing to preferentially excite the fundamental mode at the input.

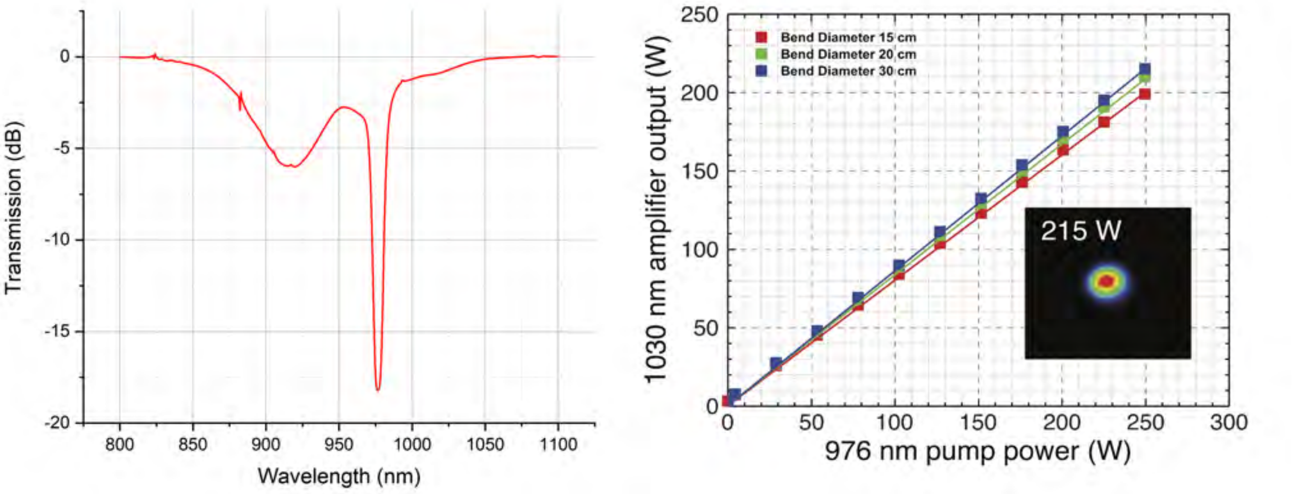

Figure 3. left: Typical transmission spectrum of the VLMA-40-220-PM-YB; Right: Amplification characteristics of the fiber in the MOPA system described in 2.2. Insert: Beam profile at the fiber output for a 215 W average power

3. HIGH POWER FCPA LASER

We have set up the VLMA-40-220-PM-YB in our in-house developed monolithic FCPA system. The main amplifier was implemented with an MFA, consisting of a single section of custom graded index (GRIN) fiber. In this section, after a brief description of the MFA, we present the FCPA system and its obtained performances.

3.1 Mode field adapter

The MFA is implemented between a PM-DC-10-130 fiber and the VLMA-40-220-PM-YB. Its role is to convert the mode field diameter (MFD) of the PM-DC-10-130 (12 µm at 1 µm wavelength) to the 32 µm MFD of the VLMA-40-220-PM-YB. A schematic implementation of the MFA is shown in Fig. 4. It's design was made using the ABCD matrix formalism for a gaussian beam.

The GRIN fiber was also drawn at Photonics Bretagne. Its cladding diameter is 200 µm to insure smooth geometrical transition between the PM-DC-10-130 and the VLMA-40-220-PM-YB. The resulting component is then recoat with a low-index polymer, and passively thermalised.

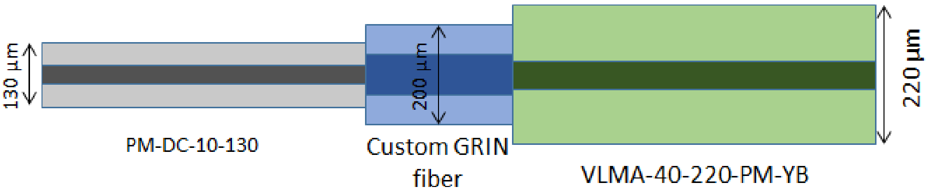

Figure 4. Schematic implementation of the mode field adapter

3.2 FCPA system

The FCPA laser operating at 1040 nm is described in Fig. 5. The system is seeded by a in-house developed all-fiber oscillator operating in the dispersion-managed soliton regime and delivering a stable pulse train at 20 MHz repetition rate. A fiber Bragg-grating is used for intra-cavity dispersion management. This SESAM-based mode locked seed oscillator delivers pre-chirped pulses of 11 ps duration, a 15 nm spectral width and 2 mW average power. The pulses are then stretched to approximatively 390 ps by means of a CFBG. A first amplification stage is used to counterbalance the losses of the stretcher. To access to high energy regime, a fiber acousto-optic modulator (AOM) was placed prior to the main power amplifier in order to reduce the repetition rate, and a second amplification stage compensates the losses of the AOM.

The 4 m long VLMA-40-220-PM-YB fiber is pumped with two 35 W 976 nm multimode laser diodes through a pump combiner and the MFA described in 3.1. The end facet of the fiber is end-cap protected, made of a 230 µm diameter angle clived fused silica rod. Finally, the amplified chirped pulses are compressed with a CVBG.

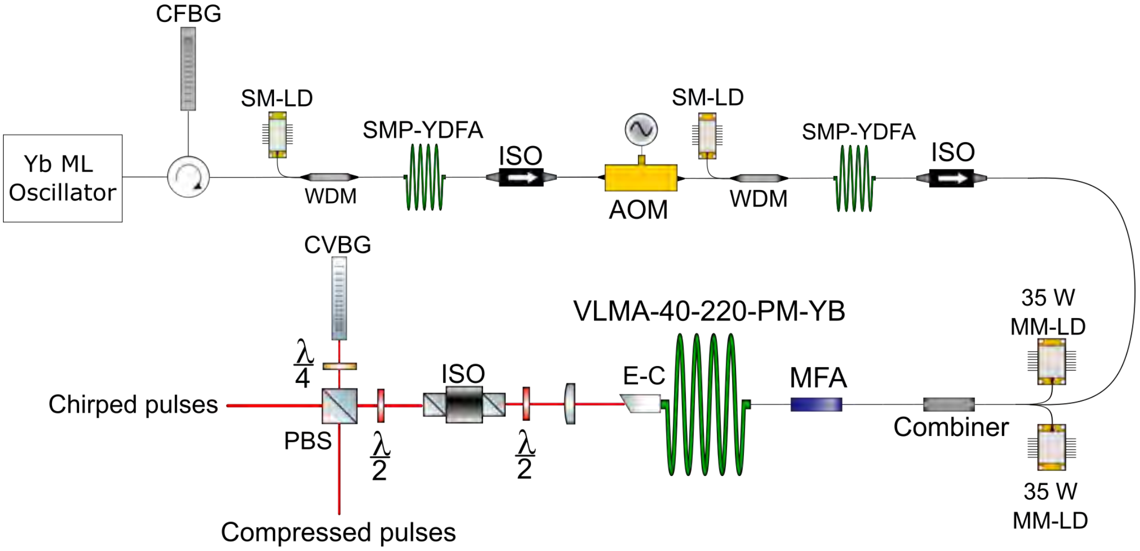

Figure 5. Schematic FCPA system. CFBG: Chiped Fiber Bragg Grating; SM-LD: Single Mode Laser Diode; WDM: Wavelength Division Multiplexer; SMP-YDFA: Single Mode Pumped Yb-doped Fiber Amplifier; ISO: Isolator; AOM: Acousto-Optic Modulator; MM-LD: Multimode Laser Diode; MFA: Mode Field Adapter; E-C: End-Cap; CVBG: Chirped Volume Bragg Grating; PBS: Polarization Beam Splitter

A dichroic mirror (not shown in Fig. 5) is used to remove the residual pump. At the fundamental repetition rate, an average power of 50 W has beeen achieved, limited by the available pump power, while keeping a good beam quality ($M^2 < 1.2$). By lowering the repetition rate to 500 kHz, 41 µJ pulses are obtained, limited by the input signal energy and the length of the fiber. By adjusting these two parameters, it would be possible to reach higher energies. The amplification results are shown in Fig. 6.

Numerical simulations based on a commercial software solving both rate equations and generalized scalar non-linear Schrödinger equation have been performed to estimate the input energies needed to improve the amplified pulses energy to 50 µJ. It appears that only 40 nJ are sufficient to obtain more than 50 µJ at the output of the amplifier. So, by adding a third preamplifier, it should become possible to achieve 50 µJ pulse energy at 500 kHz repetition rate. However, more fiber length optimization will be needed to reduce the pulses durations.

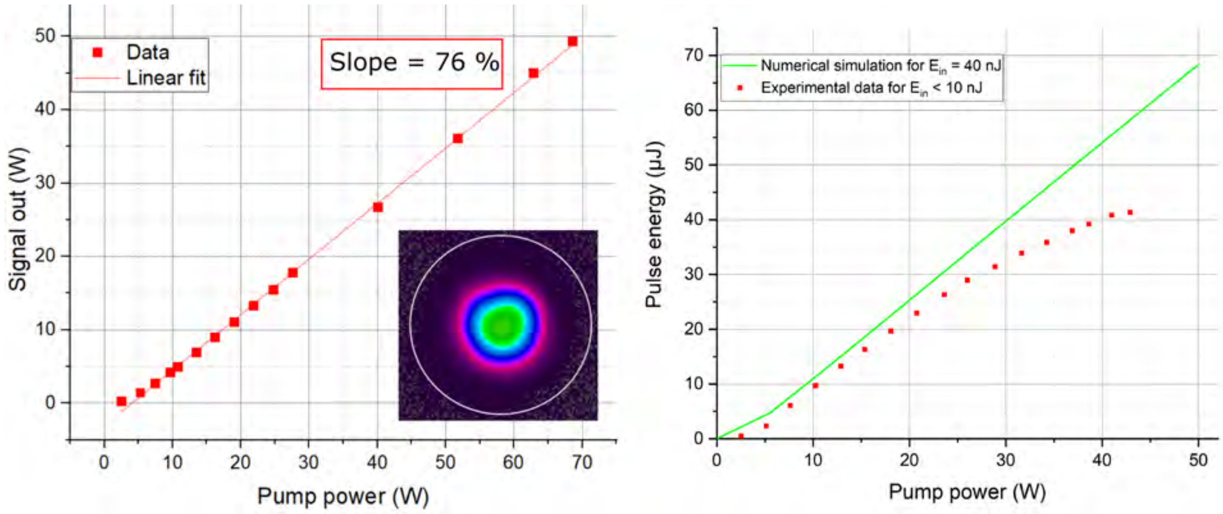

Figure 6. Left: Amplification characteristics of the main amplifier at the fundamental repetition rate. Insert: Beam profile at the fiber output for a 50 W average power; Right: Energy per pulse at a 500 kHz repetition rate

Pulse compression has been achieved with a CVBG. By tuning the CFBG, pulses duration of 540 fs were obtained. Due to the pulses spectral width (approx. 15 nm at -3 dB), it is possible to reduce the duration by adjusting the length of the fibers in the system, and drop below 500 fs durations.
The autocorrelation trace of the compressed pulses is shown in Fig. 7. We can see a remaining pedestal on the compressed pulses trace, either due to high-order dispersion (HOD) terms,[4] or the accumulated non-linear phase shift through the system.[5] On both cases, it is possible to improve pulse quality by adjusting the HOD of the system.

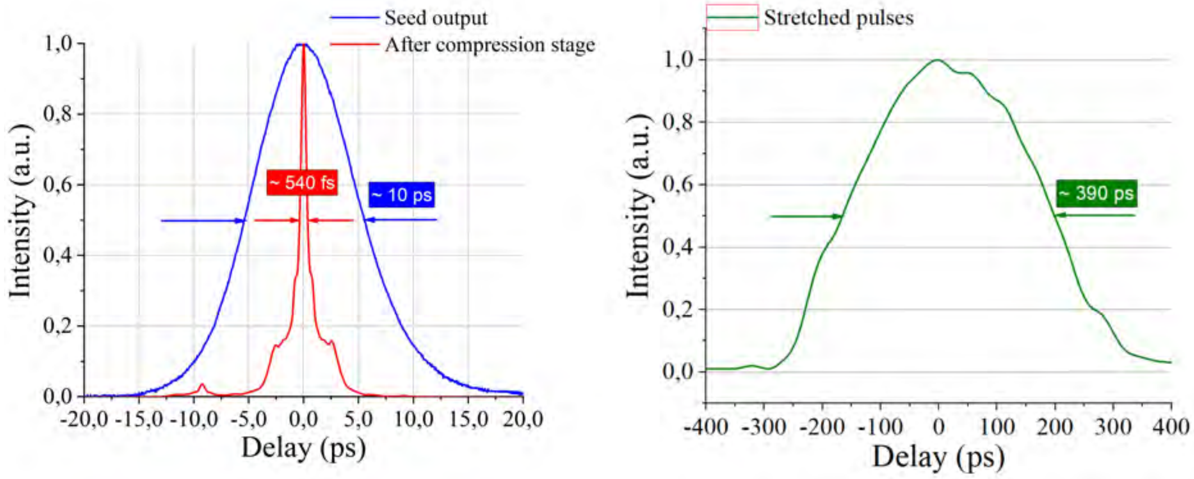

Figure 7. Left: Autocorrelation trace for the seed pulses and the compressed pulses; Right: Fast oscilloscope trace of the stretched pulses.

4. CONCLUSION

We have shown here the succesful implementation of a compact all-solid step-index PM VLMA Yb-doped fiber amplifier in a monolithic FCPA laser. The fiber design makes it easier to use compared to competing photonic crystal fibers. Energies up to 41 µJ at high repetition rate were obtained, paving the way to high reliability energetic laser for outside the laboratory usage. We also shown that further optimization of passive fiber length and input signal power should allow shorter pulses and higher energies.

5. ACKNOWLEDGEMENTS

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