# High power Yb:YAG single-crystal fiber amplifiers for femtosecond lasers

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## ABSTRACT

We describe a multi-stages single crystal fiber (SCF) amplifier for the amplification of femtosecond pulses with radial or azimuthal polarization in view of high speed material processing (surface structuring, drilling). We demonstrate a three stages diode-pumped Yb:YAG single crystal fiber amplifier to achieve femtosecond pulses at an average power of 85W at 20 MHz in radial and azimuthal polarization.

## 1. INTRODUCTION

This work has been done in the context of European project called Ultrafast Razipol. The main goal of the Ultrafast Razipol project is to demonstrate laser material processing at unprecedented levels of productivity and precision using beams with radial and/or azimuthal polarization. The ultrafast laser source is based on a master oscillator power amplifier (MOPA) concept and combines three different technologies to achieve high energy / high average power pulses. For the high repetition rate version (20MHz), a femtosecond oscillator from JDSU with moderate average power is used as a seed. Then a first amplification stage based on single crystal fiber, realized by Laboratoire Charles Fabry (LCF) and the company Fibercryst, is used to boost the average power from around 1.5W to more than 70W in order to supply the last amplification stage. The Institut für Strahlwerkzeuge (IFSW) is in charge of the development of the final amplifier stage based on thin disk technology which enables average powers in excess of 500 W. This paper is dedicated to the presentation of the performances of the single crystal fiber amplifier.

Diode-pumped Yb-doped solid-state lasers implemented in MOPA configuration clearly dominate the field of high average pulsed laser. Thanks to a very efficient thermal management and a high overlap between pump and signal beams brought by the pump guiding, the single crystal fiber (SCF) technology has recently shown strong potentialities for the amplification of ultrashort pulses. The three partners, IFSW, LCF and Fibercryst, have recently demonstrated the amplification in CW regime of beams with radial and azimuthal polarization in a single crystal fiber [1]. Beams with radial and azimuthal polarization with up to 100W power could be extracted from a 40mm long and 1mm diameter single crystal Yb:YAG using a 32W power Yb:YAG thin-disk laser as seed laser corresponding a gain factor of 3. Furthermore, in pulsed regime, the non-guided signal wave reduces strongly the non-linear effects versus advanced short pulse large mode area fiber amplifiers. Amplification of 10MW peak power pulses already has been demonstrated and the limits of this technology are still to be explored. The suitability of an Yb:YAG SCF amplifiers pumped with a high brightness diode for the amplification of ultrafast pulses in a double pass configuration leading up to 30W average power at 10MHz and up to 1mJ pulses at 10kHz rep rate with 380 fs pulses has been also proven [2].

In this work, we present the use of a series of Yb:YAG SCF amplifiers (1% Yb doped, 1mm diameter, 40mm long) to achieve high average power in radial or azimuthal sub-550fs pulses regime. Using a 1.6W power femtosecond oscillator from JDSU, more than 86W of average power in radial and azimuthal polarization with pulses with a duration of 740fs has been obtained by using three stages SCF amplifiers.

# 2. PERFORMANCES OF THE AMPLIFIERS IN LINEAR POLARIZATION

## 2.1 First SCF double-pass preamplifier stage

### *2.1.1 Experimental set-up*

The experimental setup for the first amplification stage is represented in Fig 1. The femtosecond pulses come from a JDSU Yb-based oscillator delivering a train of ultra-short pulses at a repetition rate of 20 MHz with an average power of 1.65 W and a pulse duration of 360 fs. The optical spectrum has a full width of 3.45 nm at half-maximum (FWHM) and is centered at around 1031 nm. Due to the anisotropic thermal behavior of the Yb tungstate crystal the oscillator beam shows an ellipticity rate around 50% and in order to reduce this value, two cylindrical lenses, with focal lengths of 130 mm for the first one and 300 mm for the second one, were placed at the output of the laser. After being optically isolated, a half wave plate and a polarizer are used to manage the signal power incident to the SCF. The signal is seeded into the standard 1 mm-diameter, 40 mm-long, 1%-doped Yb:YAG SCF amplifier. The SCF is mounted in a water-cooled copper heat sink. The gain medium is pumped by a 200 μm fiber coupled laser diode emitting up to 120 W at 940 nm (N.A. 0.22 with 90% of the pump power in N.A. 0.17). The pump fiber output is imaged a few mm inside the SCF on a spot diameter of 400 μm. To make the first pass amplification in a co-propagative configuration, a dichroic mirror was used to reflect the signal at 1031 nm into the SCF and pass the pump beam at 940 nm. The experimental setup is configured as a double pass SCF amplifier. A quarter wave-plate is placed after the SCF in order to obtain a 90° rotation of the polarization between the first and the second pass. This way, the output beam can be extracted by the polarizer after the second pass.

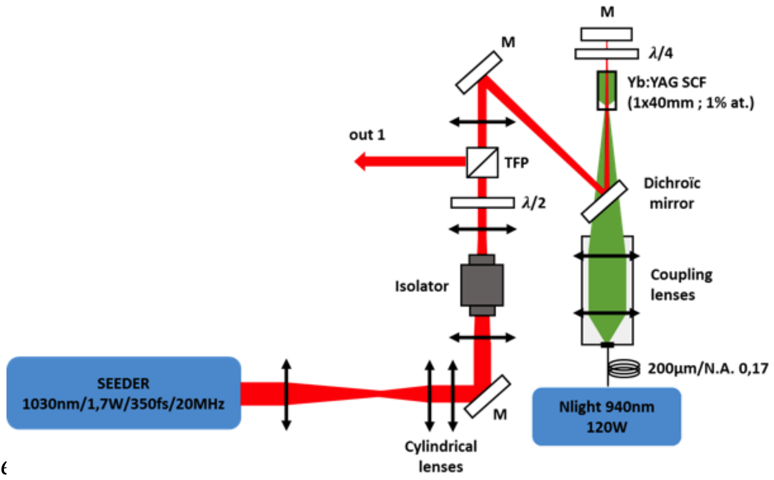


*Fig 1. Expe* *ge*

### *2.1.2 Results*

Fig 2a shows the evolution of the output power at 1030 nm as a function of the pump power at 940 nm for the single pass and the double pass amplification. For an input average power of 1.45 W (the power is slightly lower than the nominal seed laser power of 1.65W because of the losses caused by the different optical components in the beam paths) and a pump power of 120 W, we could extract 6.8 W leading to a single pass gain of 5. The maximum extracted power is tripled in the second pass with respect to the first pass and reaches 16 W for 120 W of pump power with a slope efficiency of 13%. For an input power of 10 mW, the double pass gain reached a value of about 46 (Fig 2b). Fig 2c shows the evolution of the non-absorbed pump power as a function of the incident pump power. For a maximum incident pump power of 120 W, only 3.3 W was not absorbed by the SCF. In this configuration 98% of the pump power is absorbed by the gain medium.

To finalize the characterization of the first double pass SCF amplification stage, the beam profile has been measured at maximum average power as shown on Fig 2d. M² measurement were carried out and revealed no degradation of the beam quality. At 16 W of average output power, we measured $M^2_X = 1{,}09$ and $M^2_Y = 1{,}11$ ($M^2 < 1{,}2$).

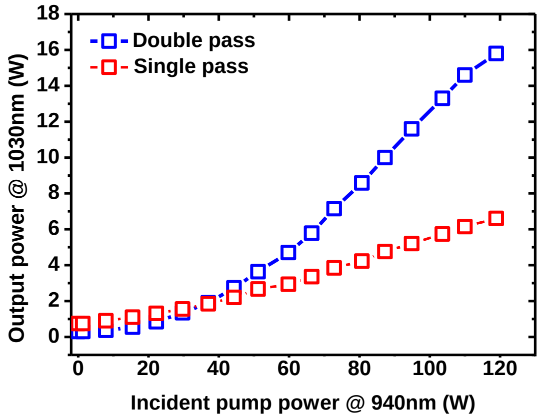


*Fig 2a. Output power after one and two passes versus pump power.*

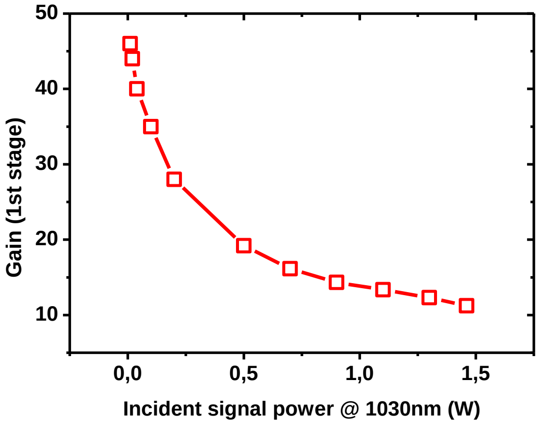


*Fig 2b. Gain of the Yb:YAG SCF amplifier versus signal input power.*

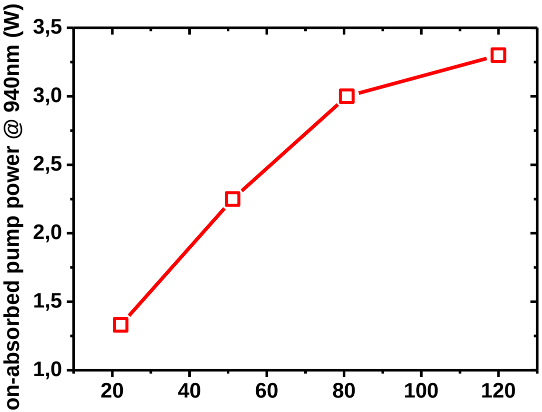


*Fig 2c. Non-absorbed pump power versus incident pump power.*

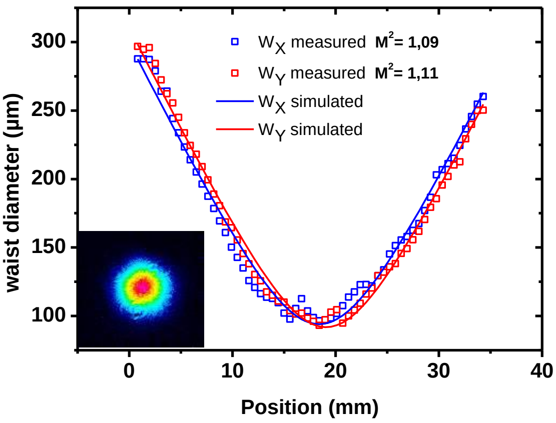


*Fig 2d. M² measurement for the two axes.*

## 2.2 **Second SCF double-pass amplifier stage**

### *2.2.1 Experimental set-up*

The first pre-amplification stage provides a maximum average power of 16 W. Due to the losses of the different optical components, the maximum input power incident on the second SCF amplifier is around 15 W. The experimental setup of the amplifier with the second booster amplifier stage is represented in Fig 3.

For this booster amplifier, the pump source is a 200 µm fiber-coupled laser diode from DILAS emitting up to 200 W at 969 nm (wavelength stabilized with external Volume Bragg Grating).

The second SCF amplifier was studied in double pass as a booster configuration. As in the first amplification stage, the signal is seeded into the SCF using a dichroic mirror highly transparent at 969 m and highly reflective at 1030 nm. This component allowed co-propagative amplification for the first pass.

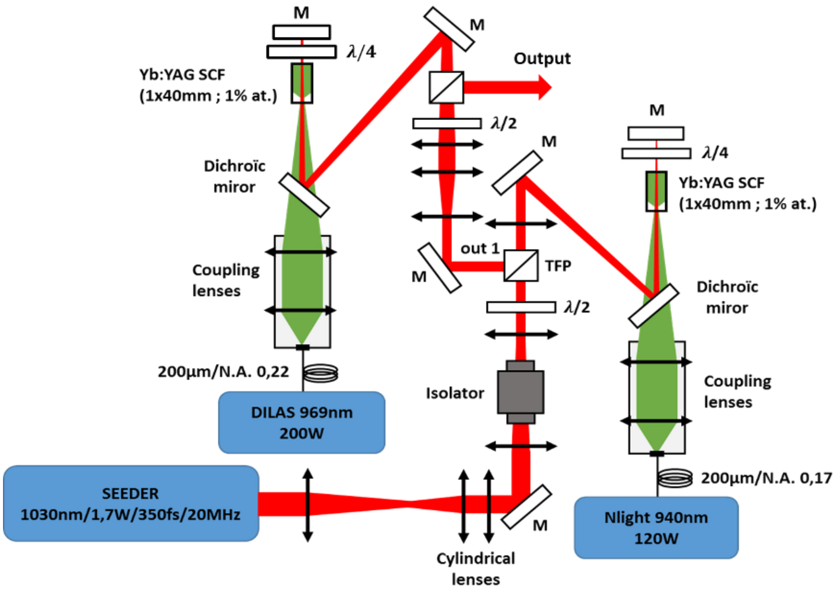


*Fig 3. Experimental setup of the HRR two-stages SCF amplifiers configuration.*

### *2.2.2 Results*

Fig 4a shows the output power at 1030 nm versus the pump power at 969 nm. For a maximum input power of 15 W on the second SCF amplifier, an output power of 52 W in single pass configuration and 72 W for the double pass configuration have been obtained for 200 W of pump power. This corresponds to a maximum gain of 4.8 at full pump power. Fig 4b shows the evolution of the single pass gain as a function of the input power at 1030 nm. For a low seed power of 2 W, a gain of 18 is measured and the output power reaches 36 W.

Fig 4d shows the beam profile after the booster amplifier and the $M^2$ measurement. The $M^2$ curves revealed small perturbation of the beam quality profile when increasing pump power. At the maximum pump intensity (200 W pump power at 969 nm), we measured $M^2_X = 1,18$ and $M^2_Y = 1,21$.

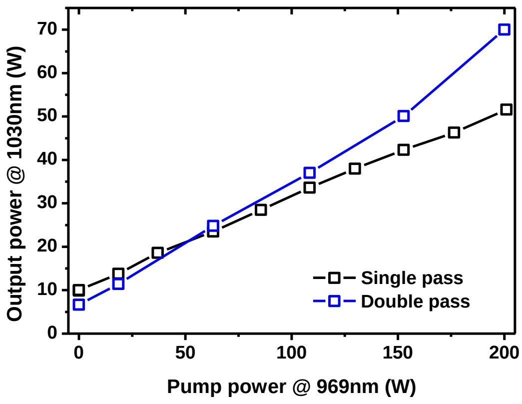


*Fig 4a. Output power after one and two passes versus pump power.*

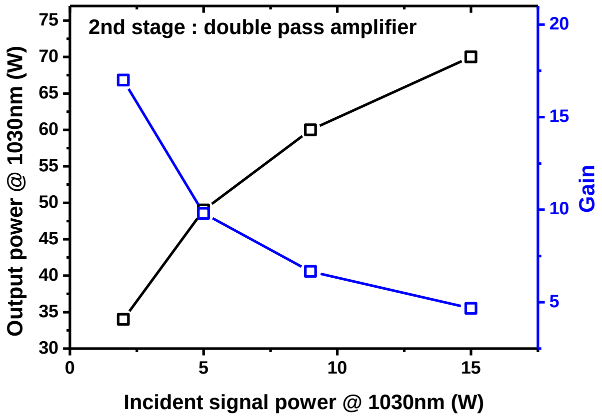


*Fig 4b. Gain of the Yb:YAG SCF amplifier versus signal input power.*

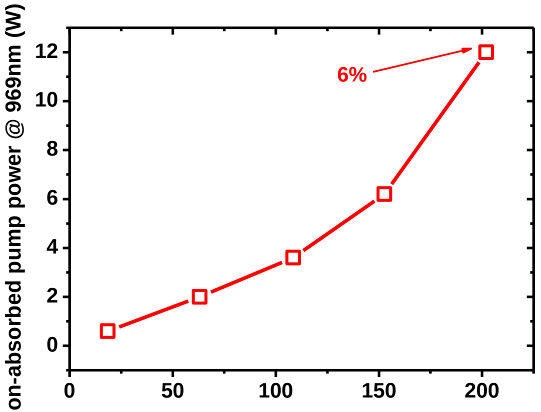


*Fig 4c. Non-absorbed pump power versus incident pump power.*

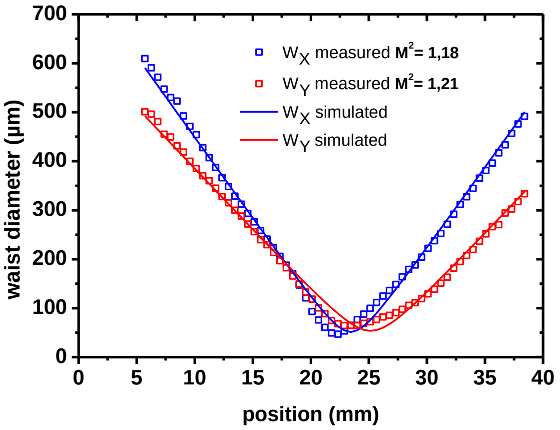


*Fig 4d. M² measurement for the two axes.*

## 3. PERFORMANCES OF THE AMPLIFIERS IN RADIAL/AZIMUTHAL POLARIZATION

### 3.1 The polarization converter

In section 2, we have obtained an average power of 70 W in a linear polarization state by using two double pass SCF amplification stages. As it is not possible to make a double pass amplification stage with an azimuthal or radial polarization, we have decided to place the polarization converter device, developed by IFSW, after the second SCF amplification stage. The polarization converter consists of an assembly of 8 segmented waveplates and the orientation of the converter element relative to the axis of the incoming linear polarization can be modified to switch from the radial polarization to the azimuthal polarization (Fig.5). The IFSW has already demonstrated the conversion of linearly polarized beam to radial/azimuthal with up to 8kW (in multimode regime) power in CW regime [3]. The same device has been successfully tested in a laser with sub-10 ps pulses and few Watts output power [4].

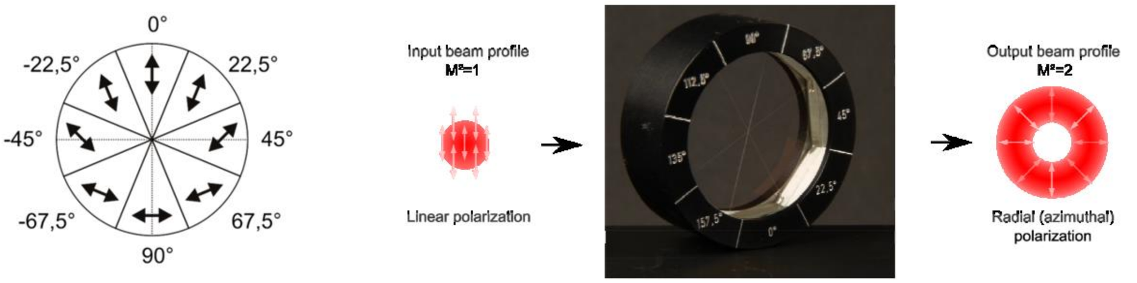


*Fig 5. Segmented wave plates assembly (8 elements) for linear to radial/azimutal polarization convertion (USTUTT)*

As the polarization converter consists of segmented waveplates, the intensity distribution is slightly distorted by diffraction effects at the junctions of the waveplates. In order to obtain a donut-shaped intensity distribution and remove the scattered light for the edges of the waveplates, a spatial filtering is implemented by focusing the beam through a small pinhole. Starting with an average power of 70 W in linear polarization state, the power decreases to 55 W after the polarization converter and the spatial filter, corresponding to around 20% of losses. A single pass SCF amplifier has to be added to compensate theses losses and to recover an average power greater than 70 W in radial/azimuthal polarization state.

### 3.1 Experimental setup

The experimental set-up (Fig. 6) is an evolution of the set-up shown in the Fig. 3. The signal is sent into the third 1mm-diameter, 40 mm-long 1% Yb:YAG SCF. As for the two previous amplifier stages, the third SCF is mounted in water-cooled copper heat sink. The gain medium is pumped by a 200µm fiber coupled laser diode emitting up to 120 W at 940 nm (N.A. 0.22 with 90% of the pump power in N.A. 0.17).

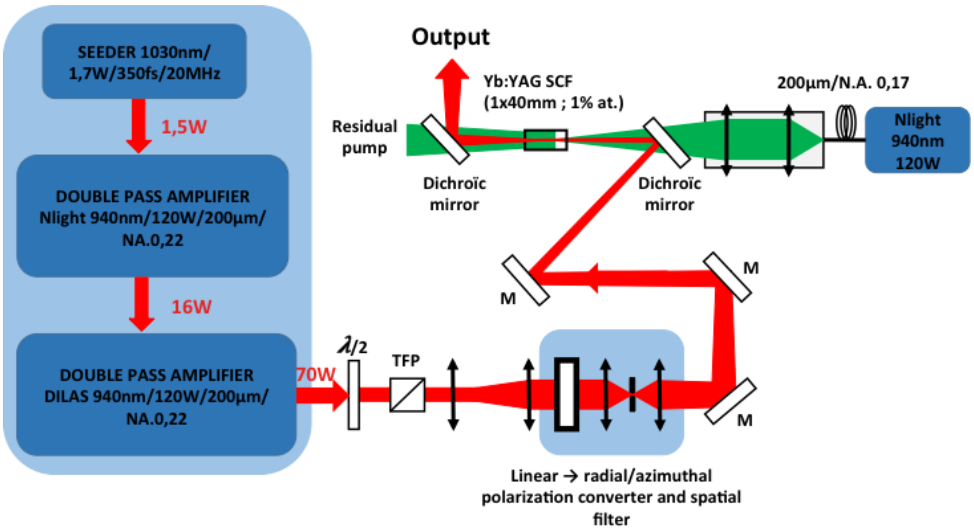


*Fig 6. Experimental set-up for the amplification in radial / azimuthal polarization state.*

### 3.3 Results

As shown in Fig 7, the amplified signal beam reached 86W at the maximum input power of 50 W and 120 W of pump power for both radially and azimuthally polarized seed. This corresponds to a single pass gain of 1.5 which is comparable to the single pass achieved for the linearly polarized seed laser at this level of signal and pump powers. At a pump power of 81 W, the output power reaches 70 W with a good quality donut shaped beam profile (point d on the Fig. 8). A maximum power of 86 W has been obtained for 120 W of pump power, but at this level of pump power, we observed a slight degradation of the beam profile.

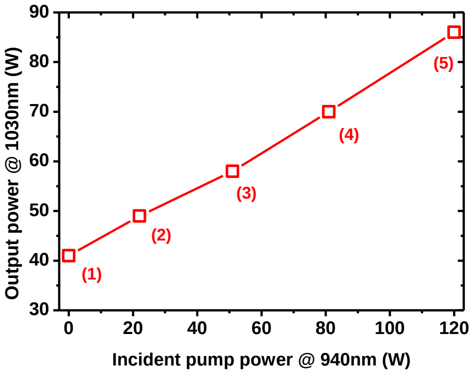
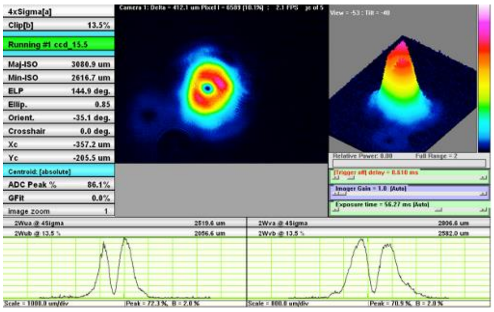
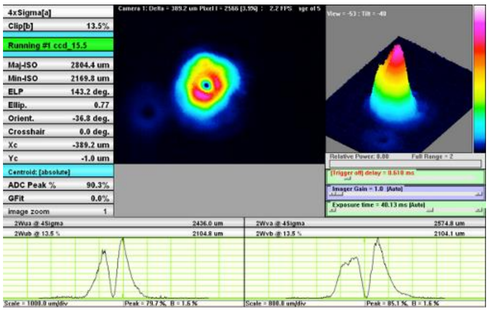


*Fig 7. Output power in radial / azimuthal polarization state after the third SCF amplifier versus the pump power and for an input power of 50 W.*



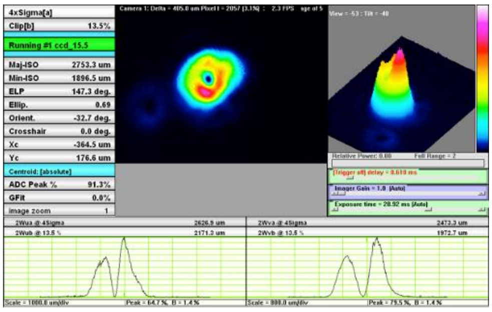
```
4xSigma[a]
Clip[b]            13.5%
Running #1 ccd_15.5
Maj-ISO          3080.9 um
Min-ISO          2616.7 um
ELP              144.9 deg.
Ellip.             0.85
Orient.          -35.1 deg.
Crosshair          0.0 deg.
Xc              -357.2 um
Yc              -205.5 um
Centroid: [absolute]
ADC Peak %        86.1%
GFit               0.0%
image zoom            1
Camera 1: Delta = 412.1 um Pixel I = 6589 [10.1%] :   2.1 FPS
View = -53 : Tilt = -40
Relative Power: 0.00     Full Range = 2
[Trigger off] delay = 0.610 ms
Imager Gain = 1.0 [Auto]
Exposure time = 56.27 ms [Auto]
2Wua @ 4Sigma     2519.6 um     2Wva @ 4Sigma     2806.6 um
2Wub @ 13.5 %     2056.6 um     2Wvb @ 13.5 %     2582.0 um
Scale = 1000.0 um/div   Peak = 72.3 %, B = 2.0 %     Scale = 800.0 um/div   Peak = 70.9 %, B = 2.0 %
```

a. *Ip = 0A ; Pp = 0W ; Pout = 41W*



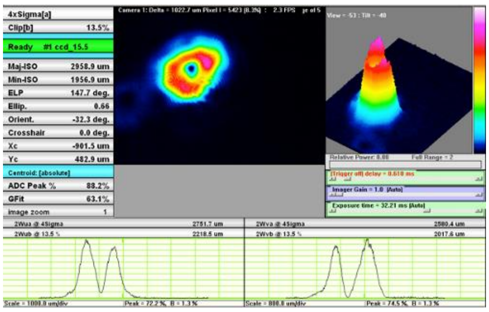
```
4xSigma[a]
Clip[b]            13.5%
Running #1 ccd_15.5
Maj-ISO          2804.4 um
Min-ISO          2169.8 um
ELP              143.2 deg.
Ellip.             0.77
Orient.          -36.8 deg.
Crosshair          0.0 deg.
Xc              -389.2 um
Yc                -1.0 um
Centroid: [absolute]
ADC Peak %        90.3%
GFit               0.0%
image zoom            1
Camera 1: Delta = 389.2 um Pixel I = 2566 [3.9%] :   2.2 FPS
View = -53 : Tilt = -40
Relative Power: 0.00     Full Range = 2
[Trigger off] delay = 0.610 ms
Imager Gain = 1.0 [Auto]
Exposure time = 40.13 ms [Auto]
2Wua @ 4Sigma     2436.0 um     2Wva @ 4Sigma     2574.8 um
2Wub @ 13.5 %     2104.8 um     2Wvb @ 13.5 %     2104.1 um
Scale = 1000.0 um/div   Peak = 79.7 %, B = 1.6 %     Scale = 800.0 um/div   Peak = 85.1 %, B = 1.6 %
```

b. *Ip = 2A ; Pp = 22W ; Pout = 49W*



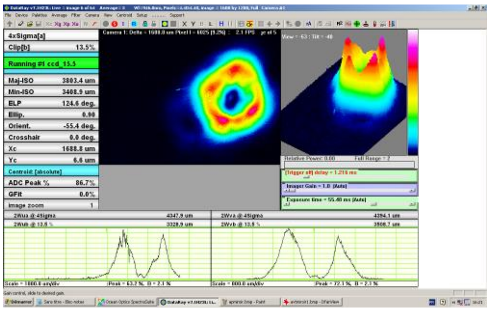
```
4xSigma[a]
Clip[b]            13.5%
Running #1 ccd_15.5
Maj-ISO          2753.3 um
Min-ISO          1896.5 um
ELP              147.3 deg.
Ellip.             0.69
Orient.          -32.7 deg.
Crosshair          0.0 deg.
Xc              -364.5 um
Yc               176.6 um
Centroid: [absolute]
ADC Peak %        91.3%
GFit               0.0%
image zoom            1
Camera 1: Delta = 405.0 um Pixel I = 2057 [3.1%] :   2.3 FPS
View = -53 : Tilt = -40
Relative Power: 0.00     Full Range = 2
[Trigger off] delay = 0.610 ms
Imager Gain = 1.0 [Auto]
Exposure time = 28.92 ms [Auto]
2Wua @ 4Sigma     2626.9 um     2Wva @ 4Sigma     2473.3 um
2Wub @ 13.5 %     2171.3 um     2Wvb @ 13.5 %     1972.7 um
Scale = 1000.0 um/div   Peak = 64.7 %, B = 1.4 %     Scale = 800.0 um/div   Peak = 79.5 %, B = 1.4 %
```

c. *Ip = 4A ; Pp = 51W ; Pout = 59W*



```
4xSigma[a]
Clip[b]            13.5%
Ready    #1 ccd_15.5
Maj-ISO          2958.9 um
Min-ISO          1956.9 um
ELP              147.7 deg.
Ellip.             0.66
Orient.          -32.3 deg.
Crosshair          0.0 deg.
Xc              -901.5 um
Yc               482.9 um
Centroid: [absolute]
ADC Peak %        88.2%
GFit              63.1%
image zoom            1
Camera 1: Delta = 1022.7 um Pixel I = 5423 [8.3%] :   2.3 FPS
View = -53 : Tilt = -40
Relative Power: 0.00     Full Range = 2
[Trigger off] delay = 0.610 ms
Imager Gain = 1.0 [Auto]
Exposure time = 32.21 ms [Auto]
2Wua @ 4Sigma     2751.7 um     2Wva @ 4Sigma     2580.4 um
2Wub @ 13.5 %     2218.5 um     2Wvb @ 13.5 %     2017.6 um
Scale = 1000.0 um/div   Peak = 72.2 %, B = 1.3 %     Scale = 800.0 um/div   Peak = 74.5 %, B = 1.3 %
```

d. *Ip = 6A ; Pp = 81W ; Pout = 70W*



```
4xSigma[a]
Clip[b]            13.5%
Running #1 ccd_15.5
Maj-ISO          3803.4 um
Min-ISO          3408.9 um
ELP              124.6 deg.
Ellip.             0.90
Orient.          -55.4 deg.
Crosshair          0.0 deg.
Xc              1688.8 um
Yc                 6.6 um
Centroid: [absolute]
ADC Peak %        86.7%
GFit               0.0%
image zoom            1
Camera 1: Delta = 1688.8 um Pixel I = 6025 [9.2%] :   2.1 FPS
View = -53 : Tilt = -40
Relative Power: 0.00     Full Range = 2
[Trigger off] delay = 1.216 ms
Imager Gain = 1.0 [Auto]
Exposure time = 55.40 ms [Auto]
2Wua @ 4Sigma     4347.9 um     2Wva @ 4Sigma     4394.1 um
2Wub @ 13.5 %     3328.9 um     2Wvb @ 13.5 %     3508.7 um
Scale = 1000.0 um/div   Peak = 63.7 %, B = 2.1 %     Scale = 800.0 um/div   Peak = 72.1 %, B = 2.1 %
Gain control, slide to desired gain.
```

e. *Ip = 8,8A ; Pp = 120W ; Pout = 86W*

*Fig 8. Spatial behavior of the amplified cylindrically polarized beam versus pump power for 5 ouput power conditions (see figure 20) Ip : operating current of the pump power of the third stage, Pp : pump power, Pout : output power.*

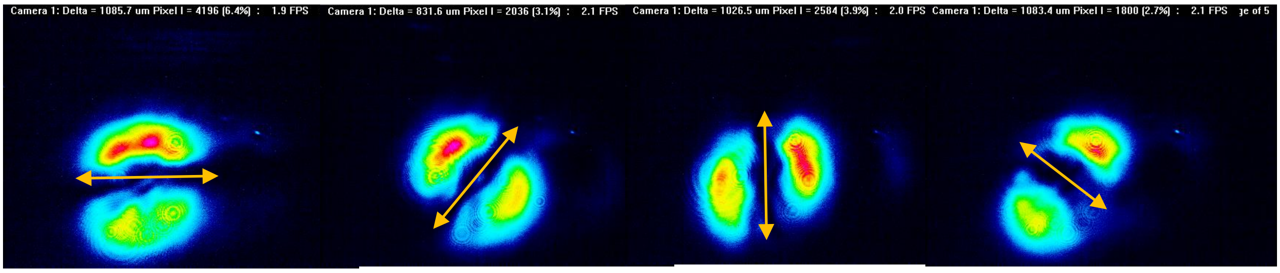


*Fig 9. Intensity distribution of the 84 W amplified beam with rotation of the analyzer axis.*

### 3.4 Spectral and temporal properties of the amplified pulses

In this part we present the spectral and temporal properties of the amplified pulses. In order to see the effect of the gain induced spectral narrowing, we measured the spectrum of the pulses after each amplification stage. The global gain after the double pass SCF amplifier for a pump power of 120 W at 940 nm corresponds is 11. The total gain after the two double-pass amplification stages and the final simple pass amplifier is around 56 by taking into account the losses.

Fig 10 shows the evolution of the spectral bandwidth (FWHM) with respect to the gain. The spectral FWHM decreases from 3.45 nm at the oscillator output to 2.4 nm for a gain of 11 and to 1.7 nm for a gain of 56, i.e., at the maximum extracted power of 86W.

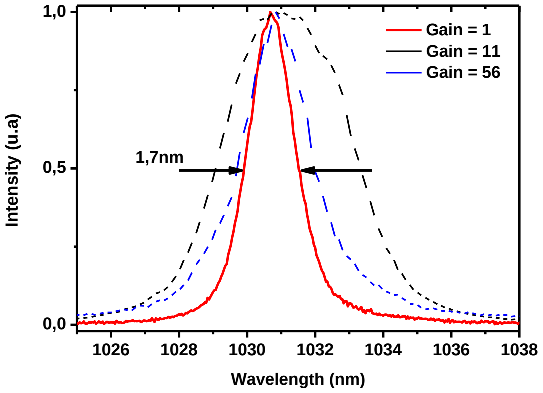


*Fig 10. Spectrum of the pulses delivered by the HRR oscillator (gain of 1), after the first amplifier (gain of 11) and after the second amplifier (gain of 56).*

Finally, by using a second second order autocorrelator, we have characterized the amplified pulses in the cylindrical polarization state. Pulses of 738 fs, assuming a hyperbolic secant temporal shape have been measured (Fig. 11).

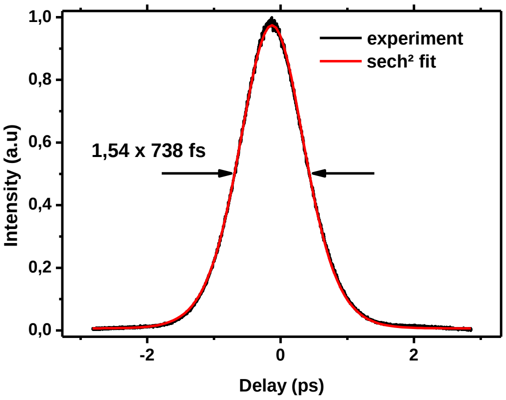


*Fig 11. Autocorrelation trace of the amplified cylindrically polarized pulses.*

In conclusion, we have demonstrated the amplification at high repetition rate of femtosecond pulses in Single Crystal Fibers modules (TARANIS from Fibercryst). A double pass pre-amplifier followed by a double pass booster has produced an average power of 70 W in linear polarization. Then a linear to cylindrical (radial or azimuthal) polarization converter has been implemented and a third stage has been needed to compensate the losses introduced by the polarization conversion. An average power up to 86 W has been obtained with sub-picosecond pulses in radial and azimuthal polarization.

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## References

[1] S. Piehler, X. Délen, M. Rumpel, J. Didierjean, N. Aubry, Th. Graf, F. Balembois, P. Georges and M. Abdou Ahmed, "Amplification of cylindrically polarized laser beams in Yb:YAG single crystal fiber amplifiers", accepted for publication into Optics Express.

[2] X. Délen, Y. Zaouter, I. Martial, N. Aubry, J. Didierjean, C. Hönninger, E. Mottay, F. Balembois, P. Georges "Yb:YAG single crystal fiber power amplifier for femtosecond sources" Optics Letters, Vol. 38, Issue 2, pp. 109-111 (January 2013).

[3] Florian Enderli and Thomas Feurer, "Radially polarized mode-locked Nd:YAG laser," Opt. Lett. **34**, 2030-2032 (2009).

[4] M. Kraus et al., “Microdrilling in Steel using Ultrashort Pulsed Laser Beams with Radial and Azimuthal Polarization” Opt. Exp. 18, N°21, 2305-22313, 2010 .