3.1 Publishable summary

The aims of the Ultrafast_RAZipol project were to demonstrate laser material processing at unprecedented levels of productivity and precision using beams with cylindrical (radial and/or azimuthal) polarization. The objectives were to achieve high productivity at high levels of precision and quality.

Therefore two laser systems (master oscillator power amplifiers: MOPA) were developed in order to achieve the above targets for structuring of large area (e.g. lab-on-chip applications) and drilling of high aspect-ratio hole (e.g. spinnerets, nozzles). For the first application, a high-repetition rate (HRR) laser system providing an output power of 500 W at a repetition rate of 20 MHz (corresponding a pulse energy of 25 µJ) and a pulse duration of approximately 1 ps was developed. In the second application case (drilling of high-aspect ratio holes), where high-energy is required, the laser system (low repetition rate: LRR) was planned to deliver an average output power of 200 W, at a repetition rate of 200-500 kHz (corresponding to a pulse energy of 0.2-1 mJ) and a pulse duration of approximately 5 ps.

The laser architecture followed in Ultrafast_RAZipol combines well-established laser technologies i.e. SESAM mode-locked oscillator as seed, single-crystal fiber amplifier (SCF) as pre-amplifier and thin-disk multipass amplifier as booster.

Figure 1 gives a schematic overview of the laser architecture.

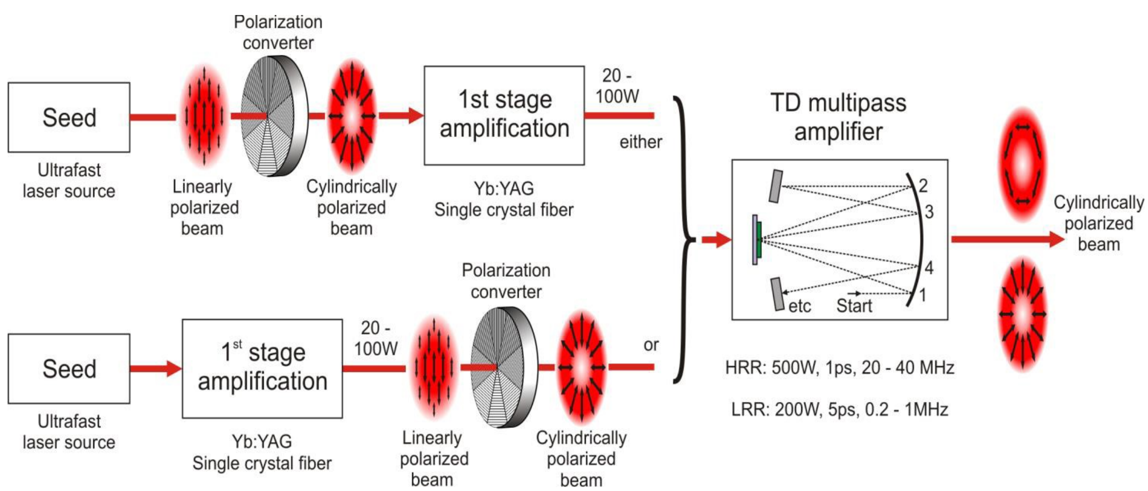

Figure 1: Schematic overview of the laser architecture

Furthermore, Ultrafast_RAZipol addresses the beam steering and shaping technologies (scanners and trepanning optics) in order for the beams to be applied to the work-piece in a well-defined application-specific manner.

The main achievements within the first period of the project can be summarized as follows.

<u>The High-repetition rate (HRR) system</u>

The focus of Ultrafast_RAZipol within the first period of the project was mainly on the development of the HRR laser amplifier chain. A bulk SESAM mode-locked oscillator delivering 2.9 W at a pulse duration of 350 fs and a repetition rate of 21 MHz (corresponding to an energy per pulse of 137 nJ) was realized by partner LUMEN. The laser oscillator delivers a linearly polarized beam with a beam quality factor which was measured to be M^2<1.2.

In a sub-sequent step, a 3-stages single-crystal amplifier was implemented to achieve a multi-10 Watts of amplified power. This has been realized in the lab of CNRS in a first step and integrated by FIB in a following step.

Within the lab experiment performed at CNRS the following results were achieved: Up to 100 W of average power at a repetition 21 MHz and a pulse duration of 700 fs in a linear polarization were extracted. The beam quality factor was measured to be <1.3 in both axes; Up to 85W of average power at a repetition 21 MHz and a pulse duration of 700 fs in a cylindrical (radial and azimuthal) polarization were achieved.

Based on the above lab experiment, FIB has realized an integrated version of the system which delivers only 61 W in a linear polarization and at a pulse duration of 680 fs.

No experiments were performed on the HRR multipass amplifier in the first period of the project. However, the complete thin-disk multipass amplifier has been assembled and tested in continuous wave (CW) regime using a 22 W intra-cavity radially polarized laser beam. A CW output power of up to 158 W could be extracted at a pump power of 600 W.

<u>The low-repetition rate (LRR) system</u>

First experiments have been performed for the LRR system within this first period. An Oscillator providing only 30 mW of stretched pulses at a repetition rate of 500 kHz could be used for the first amplification tests. An output power of 9W (M^2> 1.2) at a pulse duration of approximately 9 ps and a repetition rate of 500 kHz was extracted for the first stage of the SCF amplifier in a double-pass configuration.

In parallel to the laser development parts, the development of the polygon scanner with the appropriate coating properties for beams with radial and azimuthal polarization were started in the first period.

The main achievements during the second and final period of the project can be summarized as follows:

Radial polarisation output directly from the amplifier using thin disc laser geometry was achieved, and the long-term stability of the LRR oscillator was increased by building a more stable industrial housing.

For the LRR SCF amplifier bench, an average power of 50 W average power at 500 kHz with 9 ps pulse duration and a M^2 under 1.1 has been obtained with two SCF amplifier stages.

The concept of Divided Pulse Amplification (based on YVO4 crystals) as a passive coherent combining technique to solve the peak power limitation has been implemented.

The implementation of a new modulation scheme based on two Acousto-Optic Modulators (combination of a fast AOM before the SCF amplifier and a slow AOM after the SCF amplifier and compatible with the energy per amplified pulse) in the HRR amplifier.

On the high repetition rate system, the thin-disk multipass amplifier has achieved an output power > 500 W (resp. 400 W) at a rep-rate of 20 Mhz (resp. 10 MHz).

On the low repetition rate system, the thin-disk multipass amplifier has achieved an output power of >200 W at a rep-rate of 200 kHz (resp. 500 kHz).

Scanner hardware has been finalised and integrated in the GFH machine, and the laser-scanner integration has been realised and successfully demonstrated.

Although the potential range of material processing applications for this laser source is extremely broad, within the project, we have focused on two demonstration applications. The first application (application 1) is based on a fast scanner system which facilitates the production of complex structures like a “lab-on-a-chip” on large wafers (6” diameter). For this application, a MOPA system delivering beams with radial/azimuthal polarization with up to 580 W (resp. 415W) of average power at a repetition rate of 20 MHz (resp. 10 MHz) and a pulse duration of 782 fs (resp. 716 fs) was set up.

For application 1, the patterning results showed a good quality with sharp edges and without a damage of the glass carrier material at a high ablation rate of about 378 cm^2 per minute. Patterning large wafers with the HRR system using radial or azimuthal polarization enabled a 78 times faster processing, compared to the benchmark application. Furthermore, a 50 % higher ablation rate was achieved using radial or azimuthal instead of linear polarization. With a typical area per chip of 16 mm^2, per hour about 18 chips can be produced with the benchmark laser, while about 1400 chips per hour can be theoretically produced with the RAZipol HRR system. Taking into account, that several positioning steps have to be done during the processing, this leads to a processing cost reduction by a factor of 22.

The second application is trepanning drilling (application 2) of deep, high aspect holes with tight tolerances. In this case, a MOPA system delivering beams with radial/azimuthal polarization with up to 210W of average power at a repetition rate of 200 kHz and a pulse duration of 7.8 ps was set up.
For application 2, the benchmark experiments have shown an increase of up to 50% of the drilling efficiency using beams with azimuthal polarization when compared to beams with circular polarization.

Furthermore a 10 times faster drilling process is achieved when using the high-power LRR developed with RAZipol. This leads to a processing cost reduction by a factor 7.
Dissemination activities for Period 2 were also particularly good, with 7 papers being published. In addition to this, the Consortium has presented the results in 20 conference presentations, including, but not limited to: SPIE Photonics West; CLEO; EUROPHOTON; CLEOEurope; ASSL.

During the second reporting period, the collaboration between the Ultrafast_RAZipol partners has gone from strength to strength, supported by frequent meetings (both face-to-face and via teleconference), which reinforced an effective scientific exchange. Overall, there has been good progress towards the objectives, both on the experimental and theoretical work, and the work on all tasks was continued according to the schedule.

More information can be found on the project website: www.razipol.eu