DELIVERABLES 1.7 & 1.8

APPOLO PUBLIC REPORT Y1 & Y2

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Author(s):	**Ed. by G. Raciukaitis**
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Coordinator:

Dr. Gediminas Raciukaitis
Department of Laser Technologies
Fiziniu ir Technologijos Mokslu Centras (FTMC)
Tel: +370 5 264 48 68 Fax: 370 5 260 23 17
Address: Savanoriu Ave. 231, LT-02300 Vilnius, Lithuania
mailto: graciukaitis@ar.fi.lt
Project website: www.appolo-fp7.eu

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INTRODUCTION

The APPOLO project is establishing and coordinates connections between the end-users, which have demand on laser technologies for (micro)fabrication, knowledge accumulated in the laser application laboratories of research institutes and universities and the laser equipment manufacturers to facilitate faster validation of the process feasibility and adaptation or customization of the technology (equipment) for manufacturing conditions. The core of the consortium consists of laser application laboratories around Europe which are connected to a virtual APPOLO HUB, accumulates their knowledge and infrastructure and promotes the easy-to-access environment for development and validation of laser-based technologies. The APPOLO project cover activities on technical, technological and economical assessment of new equipment supplied by project partners in 8 complex assessment value chains and preparation of standardised procedures for the assessment service which can be provided for new project partners and customers beyond.

During the first half of the APPOLO project implementation, the consortium has established clear outlines for assessment procedures and templates. Using these procedures, partners validate new equipment by assessing them according to APPOLO HUB specified parameters. These assessments allowed partners to present their finding to customers and, therefore, gained feedback how to implement successfully assessment procedures for the desired application. The dissemination activities include training on assessment procedures, exchange of knowledge of successful assessment experiments.

RTD work was concentrated on an adaptation of equipment prototypes by their suppliers: lasers, a polygon scanner, on-line monitoring tools and small processing systems to the requirements of selected industrial application fields: photovoltaics, automotive and printing/decoration.

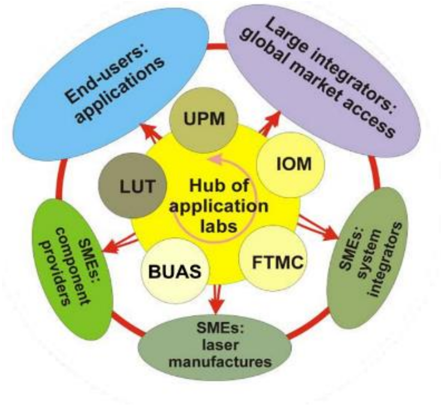
Application areas:

- Thin film photovoltaics;
- Printing and embossing;
- Machinery;
- Automotive.

The Open call for new partners and experiments was successfully implemented with seven new experiment selected, adding new application areas in general engineering and manufacturing.

Two websites for the APPOLO project are running with a permanent update of information: www.appolo-fp7.eu for all project related activities and dissemination and http://www.appolohub.eu/ for APPOLO HUB as a single access point to consolidated infrastructure and expertise of the laser application laboratories, involved in the project.

Goal of APPOLO



to exploit distributed knowledge, existing at

- academic application labs,
- equipment manufacturers,
- system integrators,
- end-users

and to enable the development of industrial laser processing for innovative products, technologies and machineries.

APPOLO Objectives

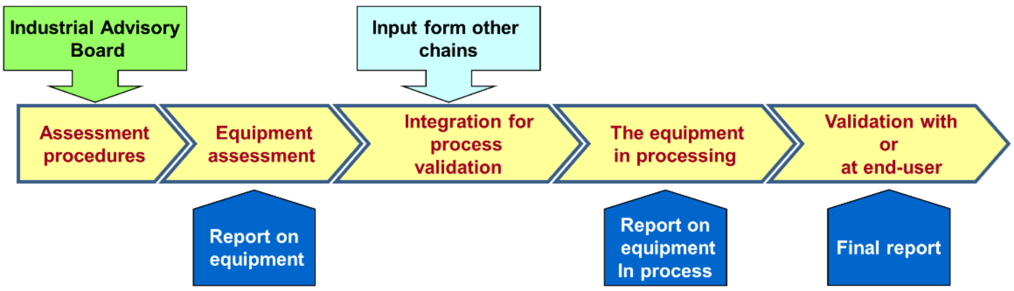
Establish and coordinate connections between

- the **end-users**, which have demand on laser technologies for (micro)fabrication;
- knowledge accumulated in the **application laboratories** of research institutes and universities;
- the laser **equipment manufacturers** (preferable SMEs: for integration, lasers, beam control and guiding, software, etc.)

Facilitate faster validation of the process feasibility, adaptation or customization of the technology & equipment for manufacturing conditions, including:

- reliability of the components;
- their interaction;
- assessment of the dedicated production processes;
- process speed, quality and repeatability;
- socio-economic issues.

15 Complex Assessment Value Chains



APPOLO HUB (www.appolohub.eu) is a network of laser application laboratories providing laser micromachining assessment services for industry partners. HUB is performing the testing activities at one in **6 laser application laboratories,** located in Switzerland, Spain, Germany, Netherlands, Finland and Lithuania.

APPOLO HUB offers service to assess and verify novel laser manufacturing technologies for industrial use.

- **Assessment of laser equipment**: We assess new lasers, scanners, beam guiding equipment and laser workstations to verify how they meet customer requirements.
- **Laser processing verification**: We offer service to define the optimal laser equipment for your samples and products with ns, ps and fs lasers.
- **Laser micromachining Ownership Costs & Benefits**: Information about costs and alternatives for ultra-short pulse laser processing: analysis and limits of laser processing parameters; process flow analysis; cost-of-ownership estimations including maintenance requirements & lifetime.

We are part of I4MS

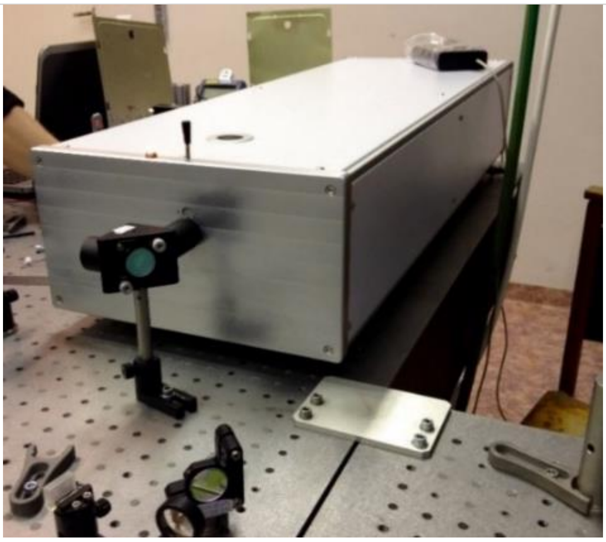
Equipment on validation in the APPOLO project

Laser companies Ekspla, Onefive GmbH, Lumentum have made significant progress in the development of updated versions of the selected ultra-short pulse laser sources planned for the assessment experiments in fast and precise surface structuring and thin-film scribing. Next Scan Technologies progressed in polygon scanners with longer scan line and smaller spot size.

High-power picosecond laser running at 1342 nm wavelength

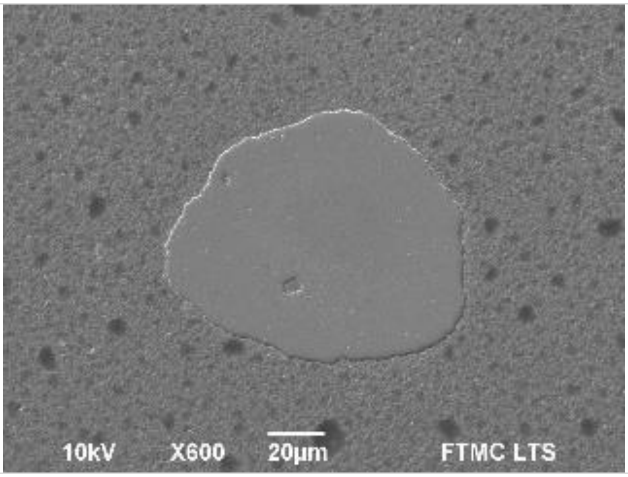
EKSPLA has developed a new concept and manufactured the high-average-power, high-repetition-rate laser emitting picosecond pulses at 1342 nm. Final laser head layout consists of a mode-locked oscillator, regenerative amplifier, and pulse output modules.

Parameter	Validated
Wavelength	1342 nm
Repetition rate	300 kHz
Average power	11 W before an AOM pulse picker
Pulse energy	37 µJ @ 300 kHz before an AOM pulse picker
Pulse duration	10.9 ps
Beam quality	M^2 = 1.03 @ 671 nm
Pulse energy stability	1.4 % St. Dev.
Polarization	Linear (s-polarisation)

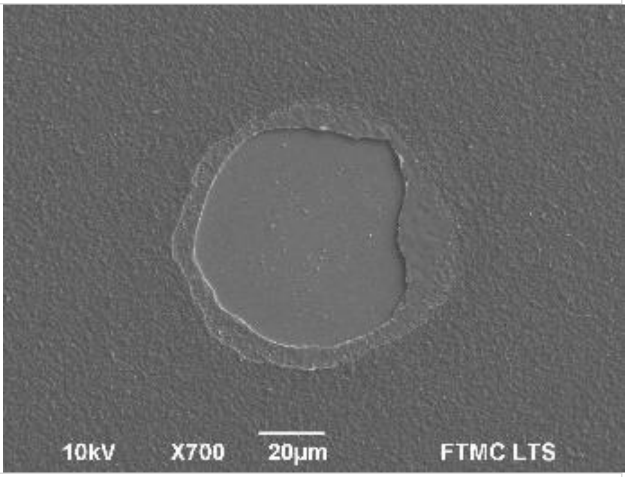


1342 nm ps-laser (Ekspla).

Assessment of the laser started at FTMC in laser scribing of CIGS thin film solar cells with a high promise in selectiveness of laser ablation.



SEM image of a crater ablated in the P2 CZTSe/Mo/SLG solar cell structure.



SEM image of a crater ablated in the P3 ZnO:Al/CdS/CZTSe/Mo/SLG solar cell structure.

Experiments showed that laser lift-off process using pulses of 1342 nm radiation wavelength is more efficient as 1064 nm pulses. Further, 47 µJ energy pulses can be successfully used to lift-off layers as thick as 1.6 µm and thinner.

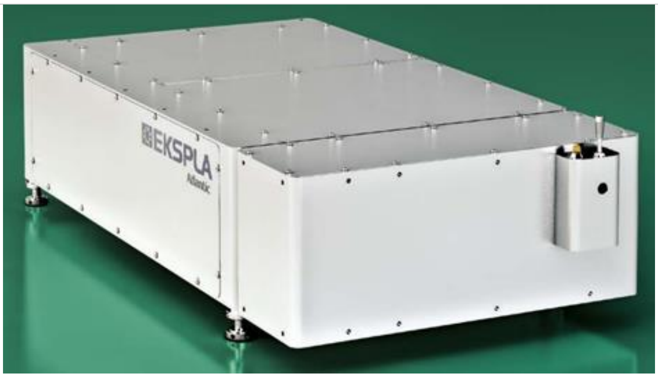
HOW TO EXPLOIT?

The 1342 nm picosecond laser is unique source of coherent radiation which was validated in selective thin film ablation but it is also promising in crystalline silicon processing for electronics. Silicon is transparent for this wavelength, making possible back-side and intra-volume processing. The laser harmonics (671 nm, 447.3 nm, 335.5 nm, 268.4 nm and 223.7 nm) provide highly intensive radiation at particular wavelengths in visible and UV range suitable for selective material processing and excitation.

High-power high-repetition-rate picosecond laser Atlantic 60

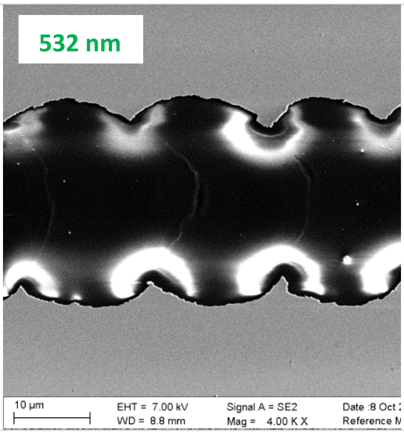
Atlantic is a new generation DPSS picosecond laser with 60 W output power at 1064 nm from Ekspla. Featuring the short pulse duration, Atlantic series laser offers minimised thermal damage to the material. Innovative design, employing fibre-based oscillator ensured excellent output beam parameters. With repetition rate up to 1 MHz, is this laser a good choice for industrial, high throughput material processing.

Parameter	Value
Wavelength	1064 nm
Repetition rate	300 kHz (up to 1 MHz)
Average power	60 W
Pulse energy	150 µJ @ 400 kHz
Pulse duration	< 13 ps
Beam quality	$M^2 < 1.3$
Pulse energy stability	1.5 % St. Dev.
Polarization	Linear, vertical 100:1

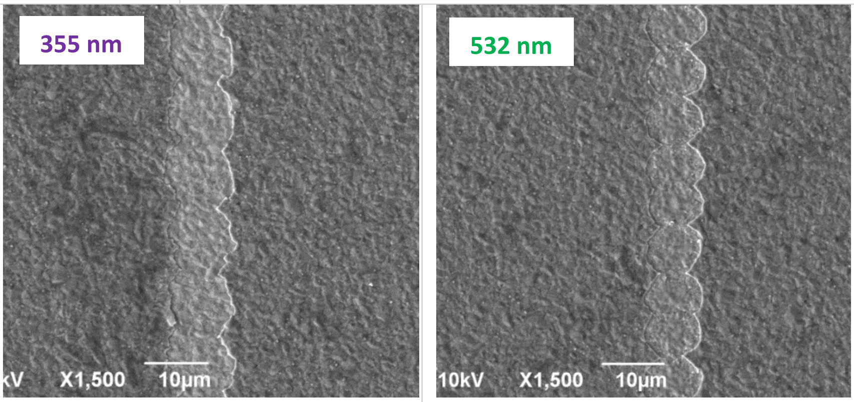


Atlantic ps-laser (Ekspla).

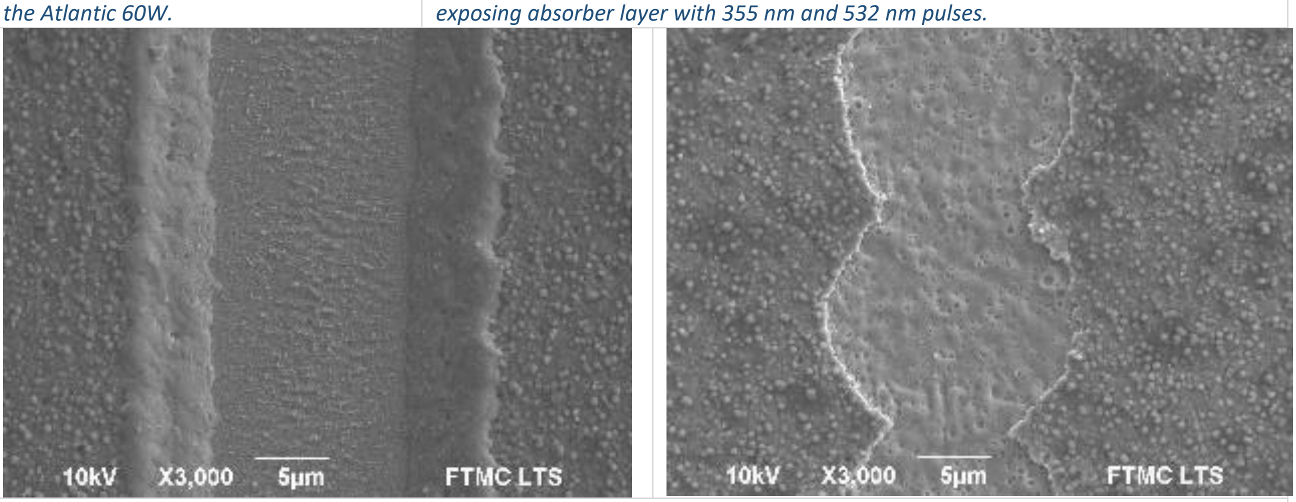
Being as a prototype at the launch of APPOLO project, the Atlantic 60 laser became the main working force in the APPOLO HUB equipment pool: thin film scribing, surface texturing or even LIFT process at different research laboratories of the APPOLO HUB.



SEM image of the P1 scribes made using the Atlantic 60W.



SEM images of single scan P3 trenches in the CZTSe solar cell structure by locally exposing absorber layer with 355 nm and 532 nm pulses.



SEM images of the P3 trenches in CIGS structure by locally exposing the molybdenum (left) or CIGS layers (right).

HOW TO EXPLOIT?

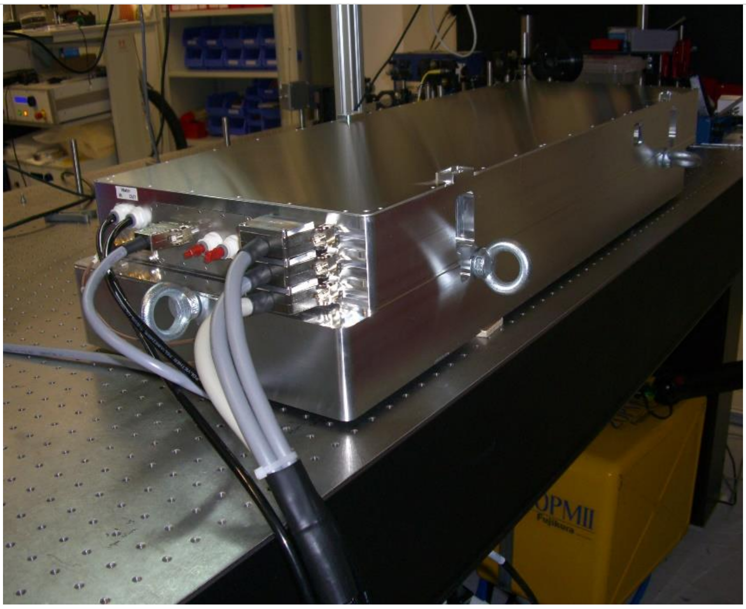
Atlantic laser was the main working force in APPOLO HUB equipment pool. It was validated in thin-film scribing, surface texturing for deep embossing and MID, metal deposition by Laser-Induced Forward Transfer (LIFT).

High power sub-ps laser for texturing from Lumentum

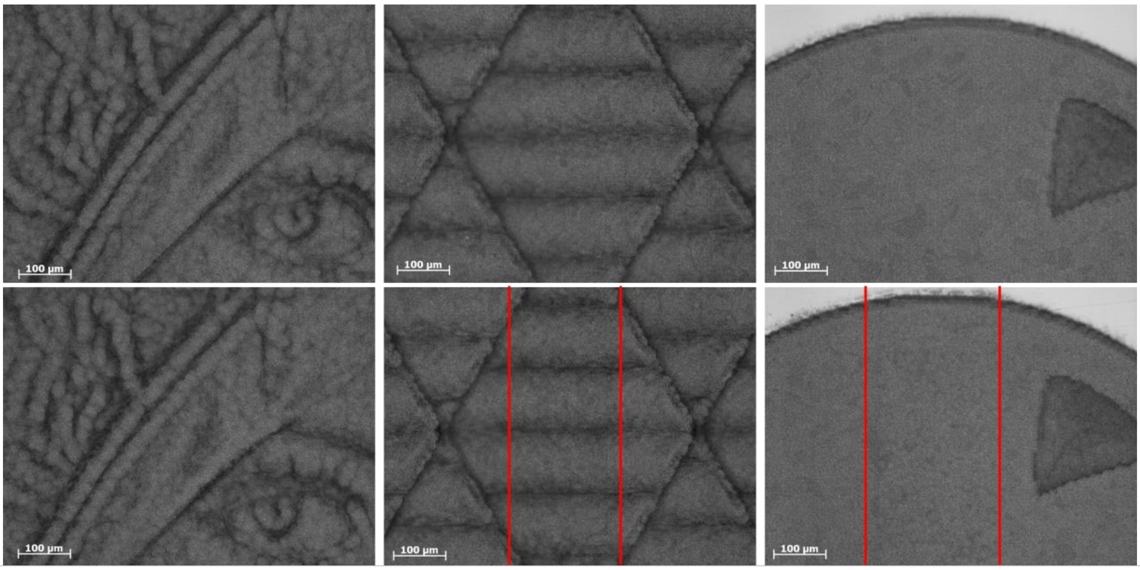
A high average power ps laser was prepared to validation by Lumentum.

Sealed seeder-housing accommodates the femtosecond laser oscillator, the AOM stage as well as a signal isolator. The sealed main housing is based on a two-sided design to accommodate the amplifier stages, pulse on demand, beam shaping, shutter, the electronics, seeder box and pump diodes. This compact industrial-grade package can manage the high thermal loads introduced by the high power pump modules and amplifiers.

Parameter	Value
Wavelength	1030 nm
Average power	100 W
Pulse duration	< 1 ps
Beam quality	$M^2 < 1.1$ after 1st stage (20 W)
Pulse repetition rate	Up to 16.2 MHz

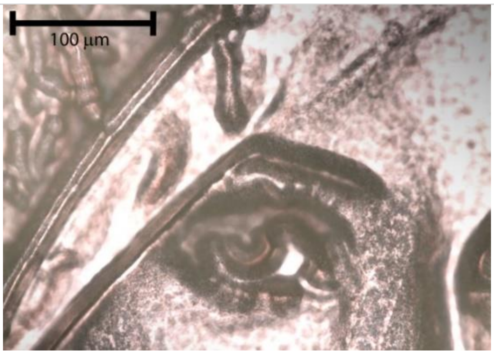


100W, 1 ps laser (Lumentum).



Light microscopy images for three different 3D-structures formed with Lumentum laser; upper row: reference pictures; lower row: stitched images.

HOW TO EXPLOIT?



Detail of machined structure 200x magnified.

For metals, the specific removal rate (removal rate per average power) increases with increasing peak fluence (or pulse energy) and reaches a maximum value when the peak fluence is at its optimum value and then drops for higher fluences.

Picture shows the result with 100 slices at 532 nm, 1 MHz, 1.2 W and 3 µm pitch. With the image size of 512 times 512 pixels and a pitch of 3 µm the image size on target is approximately 1.5x1.5 mm^2. The process time of one layer is 1.2 s and the overall process time is 2 minutes.

Customization and validation of ps-fibre laser sources

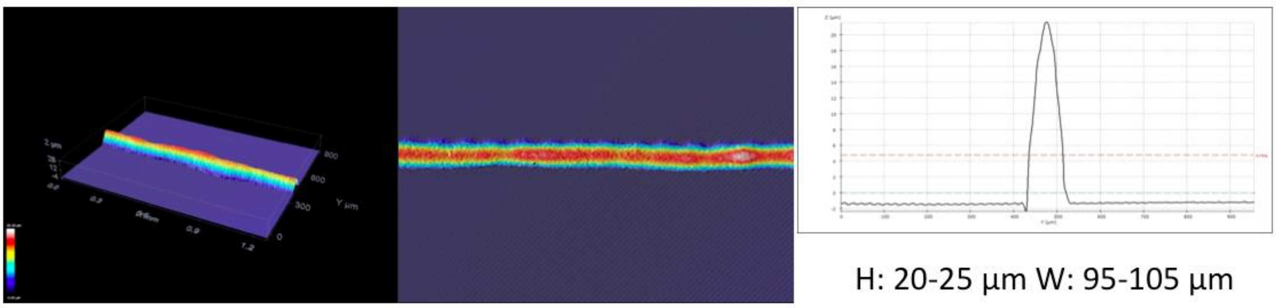
Onefive GmbH (ONE5) was working on the implementation of the constant energy mode in the high-pulse-energy fibre laser systems. The seed laser control electronics were re-designed with a high precisions frequency counting DSP system. An optimised version of Katana HP 10/05 laser was being developed at ONE5.

Based on results from first experiments with process throughput scaling made at BUAS, it was decided to focus on high pulse energy and switch to the new laser platform "Genki". The system was specifically designed towards high pulse energy (> 400 µJ) at 1064 nm with consecutive nonlinear frequency conversion. Pulses of the new seed laser have low energy fluctuations (1 % RMS) and very low pulse to pulse timing jitter (< 100 fs RMS). A built-in AOM allows arbitrary pulse selection, pulse energy adjustments "on the fly" and burst mode capabilities.

Parameter	Katana platform	Genki platform
Wavelength	1064/532 nm	1064/532/355 nm
Repetition rate	50 kHz – 10 MHz, continuously adjustable	10 kHz – 10 MHz, single pulse with pulse-picker
Average power	15 W @1064 nm 8 W @532 nm 0.5 W @355 nm @1 MHz	6.3 W @1064 nm 2.9 W @532 nm 0.8 W @355 nm @100 kHz
Pulse energy	15 µJ (1064 nm) 8 µJ (532 nm) 0.5 µJ (355 nm)@1 MHz	400 µJ (1064 nm) 280 µJ (532 nm) 160 µJ (355 nm) @10 kHz
Pulse duration	35 ps	10 ps
Beam quality	$M^2 < 1.2$	$M^2 < 1.2$

Onefive GmbH has delivered an optimised laser based on GENKI platform to BUAS for validation. The high pulse energy available supports successful BUAS approach to high-throughput CIGS scribing.

Assessment of the LIFT process was performed using ONE5 Katana ps-laser, parameterising of LIFT lines and characterization of silver pastes with added thinner.



LIFT silver paste line obtained using the ps-laser Katana integrated into the APPOLO Test-bench available at UPM. Pulse energy - 11.4 µJ; pulse repetition rate - 50 kHz; scan speed - 4.5 m/s.

HOW TO EXPLOIT?

An optimization of the high-throughput laser scribing processes is possible leading to significant improvement solar cell efficiency on module level. With the lift-off process, an extremely efficient process is introduced which has some particular characteristics.

With the new Genki laser from ONE5 a new high energy (> 400 µJ) laser source with 10 ps pulse duration became available. This laser that is well suited for scribing purposes and we will transfer newly developed high-throughput processes to the Genki XP laser.

Polygon line scanner (NST)

Next Scan Technologies improved control of its polygon line scanner and designed updated versions with reduced focused beam spot and increase line length.

The high-speed Line Scan Engine featuring the unique mirror based f-Theta optics:

- Polygon scanner provides 50 to 400 line scans per second;
- Very high laser beam scan speeds: 25 to 100 m/s and higher;
- Unique telecentric – scan beam is always perpendicular to object surface – f-Theta optics;
- 170 mm and 300 mm scan width;
- Diffraction limited quality optics providing small, focused spot sizes;
- Includes control electronics for easy integration with lasers and linear stages;
- SuperSync™ option for MOPA based lasers.

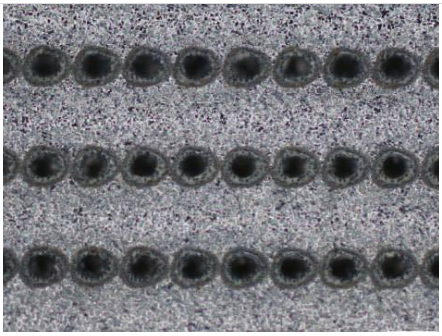
Polygon scanner LSE 300 – the scan line is extended to 300 mm.

New developments

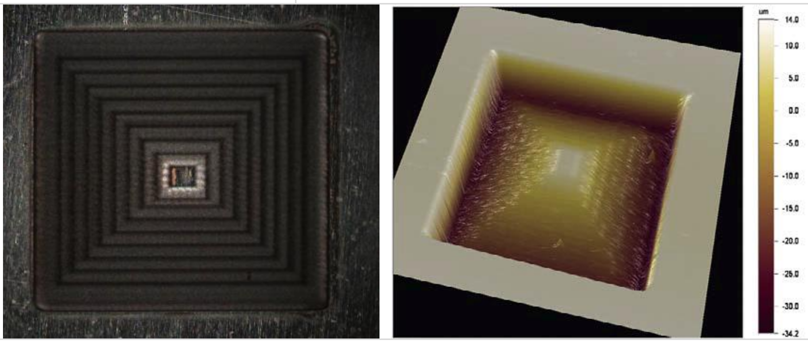
- UV optics (LSE300 available in OEM);
- TrueRaster for absolute accuracy and high line straightness;
- High NA for the smallest spot sizes on large full telecentric areas;
- Job dithering for smooth surface processing;
- Interleaving for lower rep rate pulsed lasers and material temperature control between laser pulses.

The new version of the LSE-170 lines scanner with the new firmware was tested.

Polygon scanner LSE 170 HNA.



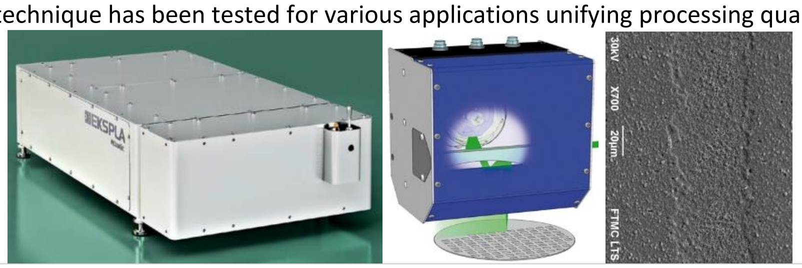
Optical microscope images of laser-polygon drilled holes in polycrystalline silicon.



Optical microscope image (left), 3D profiler images (middle) and 2D profiler profiles (right) of 3D cavity engraved in stainless steel by laser-polygon duet system.

HOW TO EXPLOIT?

Picosecond lasers in many cases have shown excellent results of material processing for diverse applications. Polygon scanner from Next Scan Technologies provides means to control laser beam in space at the speed of 100 m/s. The technique has been tested for various applications unifying processing qualities: speed, power and precision.



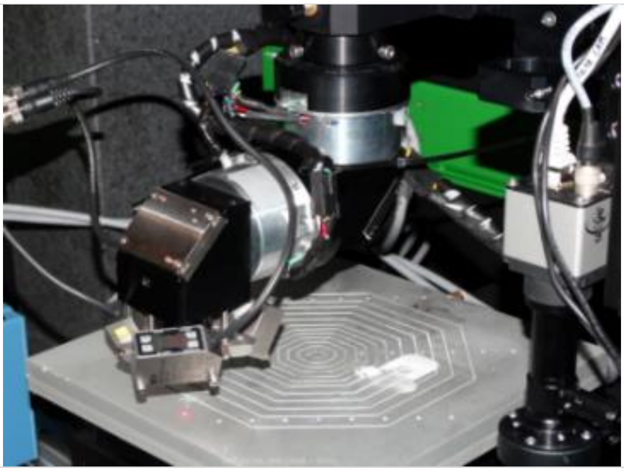
Picosecond laser Atlantic (Ekspla) and polygon scanner LSE 170 (Next Scan Technologies) provide opportunity to reach the removal of the full CIGS structure to expose the molybdenum back-contact at the scribing speed of 50 m/s.

System integration

APPOLO consortium includes partners: system integrators, large and small ones. Activities in APPOLO provided them possibility to upgrade existing products or build new machines for assessment experiments and end-user requirements.

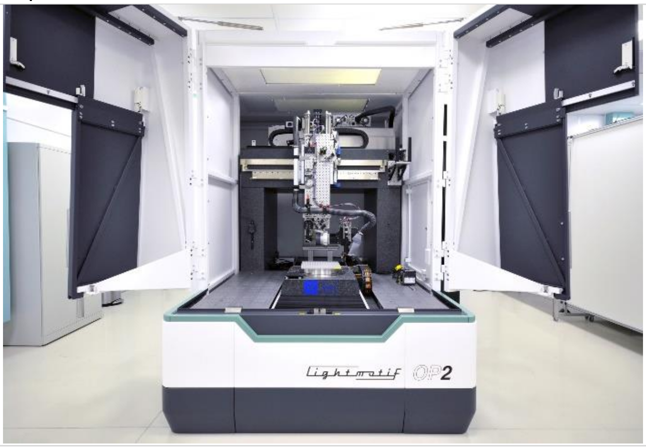
DuoMaster laser processing system of ELAS in FTMC lab.

ELAS has finished upgrading its DuoMaster laser processing system, adding new flexibility in selection of numerically controlled laser tools for processing. The whole optical part was reconstructed based on feedback from assessment experiments.



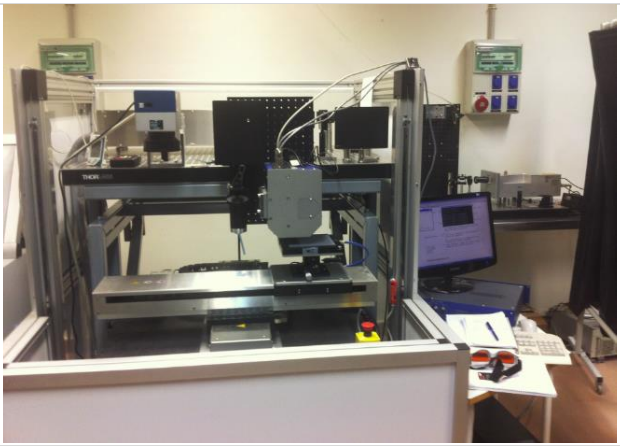
3D laser processing head ADILAW of ELAS

ELAS designed and assembled the 3D laser processing head ADILAW with the support of AMSYS on-line measuring tool. The new laser processing tool was validated in laser activation of polymer surfaces for selective metallisation.



New design laser texturing machine (Lightmotif)

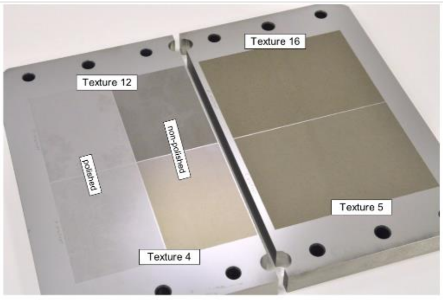
Ligthmotif progressed with laser texturing system development: the laser texturing of moulds technology was transferred from laboratory scale setup, to real industrial machine



Test-bench for UPM (Mondragon).

Mondragon prepared the bench tool for UPM – a machine for assessment of lasers, thin-film scribing and LIFT process which are important for Abengoa.

HOW TO EXPLOIT?



A flat test mould, textured with four different texture candidates.

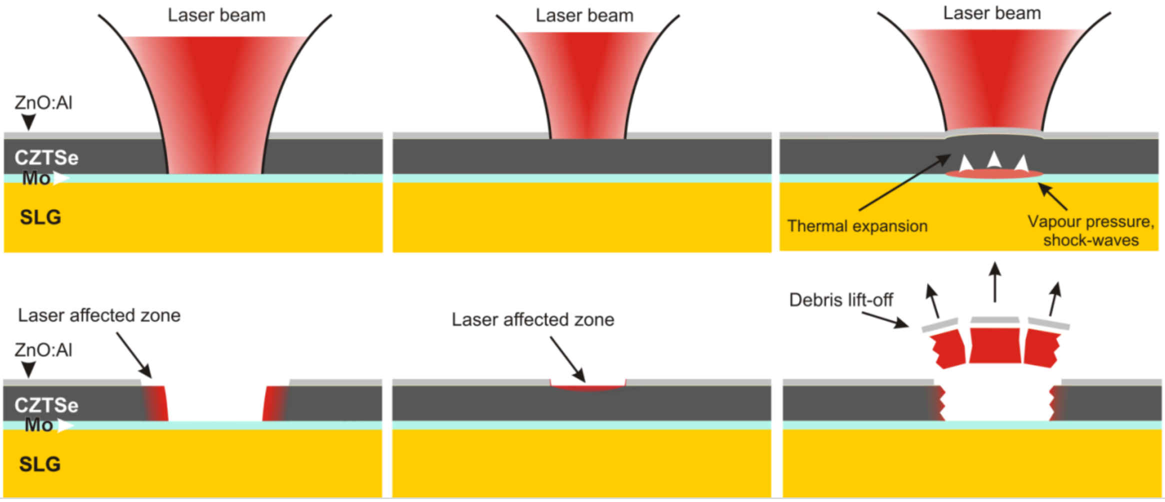
The method of distributing dimples in the tiles of a meshed surface was improved to prevent visible inhomogeneities, caused by too regular pillar distributions in the tiles.

Improvements of the laser process needs for cleaning of the laser textured mould surfaces. A new cleaning method was developed using the focused laser spot to scan over the mould surface to remove the redeposition by laser ablation.

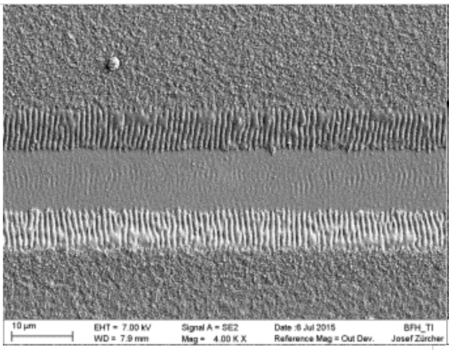
Novel thin-film scribing concepts for solar cell

Partners: FTMC, BUAS, IOM, UPM, EMPA, Ekspla, Onefive, Flisom

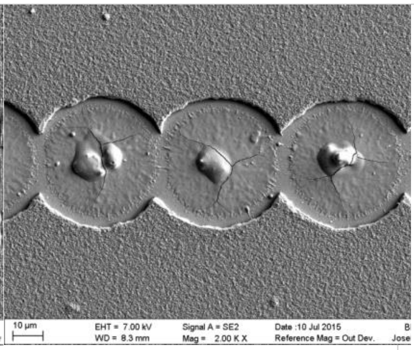
Four different routes (FTMC, BUAS, IOM, UPM) in thin-film scribing for monolithic interconnections in CIGS solar cells are running in parallel based on lasers with different pulse duration and wavelength for optimising processes based on various substrates: glass, polymer and metal foil. End-user requirements were clarified and write down as specific assessment and characterisation procedures in the validation of the equipment and the scribing processes. The progress was achieved in the fundamental background of the damage-less film removal, on-line characterisation techniques and technological approaches in minimising the “dead area” width, providing feedback to the equipment suppliers. All those activities were running during year 1 in order to prepare for the assessment of new ultra-short pulse laser sources and beam guiding technique until they will be available for the full-scale validation experiments. BUAS worked on optimising P1-3 scribing processes. In year 2, the focus was set on optimising scribing velocity with electrical validation of the achieved scribe quality. More than 1.5 m/s scribing velocity was demonstrated for the P2 process using two different scribing approaches.



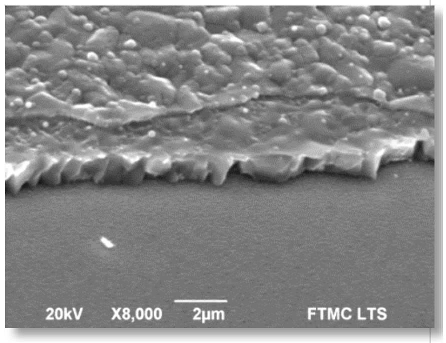
Three approaches for P3 laser scribing processes: whole stack ablation, lift-off the top contact; lift-off of whole film stack to expose Mo back contact.



SEM image of a Classical P2 process in CIGS solar cell; scan speed 150 mm/s.



SEM image of a partial lift-off P2 process. The efficient process allows scribing at 820 mm/s with a pulse repetition frequency of 20 kHz.



P3 lift-off process in CZTSe solar cell: a single pulse removal of multiple layers. Laser pulse energy: 45 µJ, 10 kHz, 1000 mm/s, 1064 nm.

Laser scribing is a way to maintain the PV module efficiency by dividing a large scale device to smaller cells interconnected in series. Three scribing processes called P1, P2 and P3 are needed for monolithic interconnection.

- Further investigations on an understanding of the “lift-off” process during laser scribing were conducted at FTMC with “standard” Ekspla lasers on different materials until the new laser is not available for assessment in the labs.
- The development of a suitable P1 process in a stack of metallic substrate/dielectric barrier/Molybdenum contact was the main challenge within the CIGS activities of APPOLO at UPM and IOM.
- Additional work was carried out for the development of the best practice laser scribing processes for CIGS scribing and assessment of the laser and the equipment.

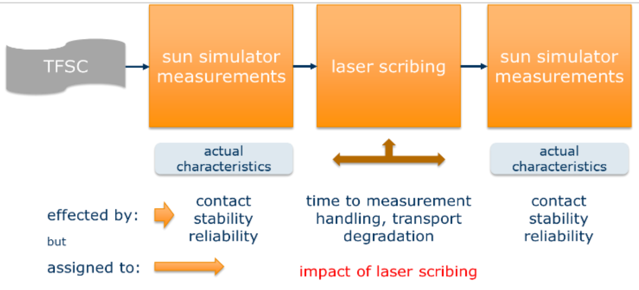
On-line control of the scribing process

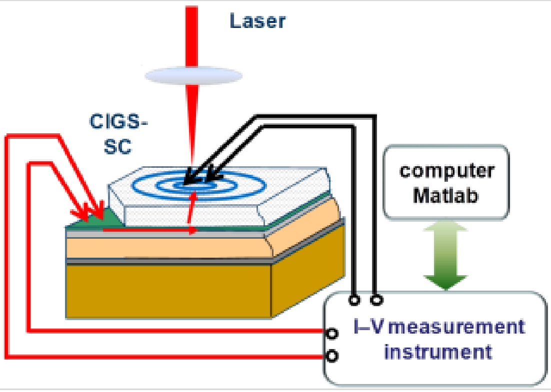
Partners: FTMC, BUAS, IOM, UPM

The high quality monolithic interconnected modules call for a small dead area, selective removal of the thin films and low losses of the interconnection area. Further, the high speed and a large process window are needed. The electrical functionalities of the laser scribes are insulation for P3 and P1 and connection for P2. These are the aims of the scribes but the laser scribing process parameters are very different. The most sensitive scribe regarding shunt formation is P3 that is the final step of monolithic interconnection.

Measurement of the solar cell properties before and after laser scribing is a usual way for the evaluation of the impact of the laser scribing to the functional characteristics. Various effects are influencing the finally electrical measurements. They may originate from the measurement equipment, the samples, and the changes of the characteristics with time. Such impacts can be hardly distinguished from the impact of the laser scribing process that should be evaluated in principle. Therefore, a misinterpretation of the final results in relation to the impact of the laser scribing process to the found changes of the electrical characteristics is simply possible.

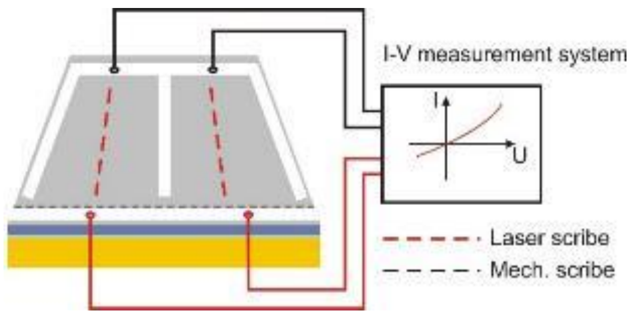
IOM spent most of the time during the first year of implementation in preparation and validation of the online monitoring tool for laser scribing with nested circular scribes.



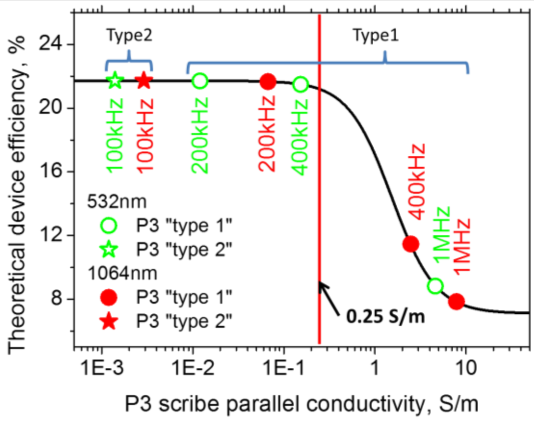


The new method of on-line electrical characterisation of thin film solar cells during laser scribing process was developed by FTMC. Laser processing of CIGS solar cells can induce undesirable shunting paths resulting lower module efficiencies.

A technique for electrical characterization of the laser scribe can be implemented at the early stages of the laser process development, and the scribe specific conductivity values can be extracted by fitting the results with a simple linear function (LLST).



Setup of the Linear Laser Scribing Technique (LLST) for in-process parallel resistance measurement in a fully functional mini-cell.



PV efficiency dependence on the shunt resistance due to the P3 laser.

HOW TO EXPLOIT?

The methods of the evaluation of the parallel resistance R_p of the laser scribe were applied seeking correlation between the laser scribing parameters and R_p. They revealed limitations in upscaling the scribing speed with increasing pulse repetition rate of the laser, even preserving a constant pulse overlap. Comparison of various P3 and P2 scribing approached are possible utilising those methods.

High speed & precision laser texturing

Partners: BUAS, Lumentum, Daetwyler

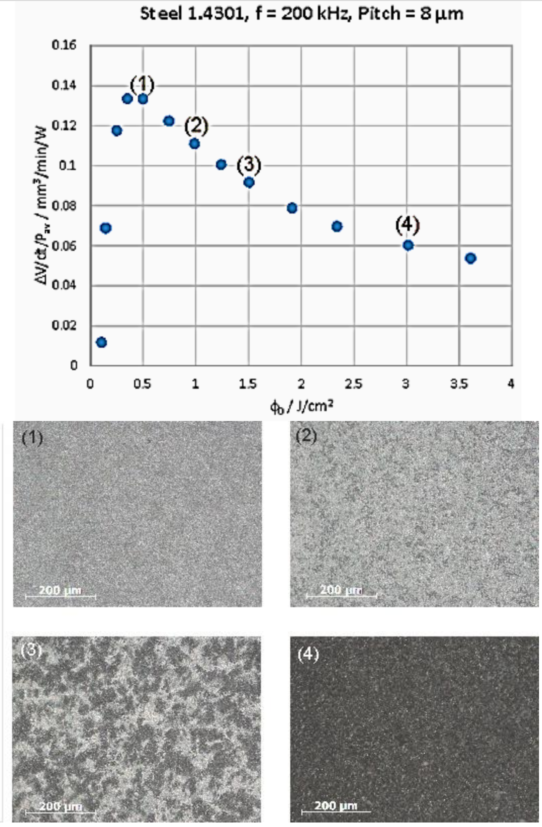
High precision and efficiency is related with efficient use of laser energy. Detailed investigations on influence laser fluence, scanning speed and overlap on volumetric removal rate and surface morphology approved the proposed model which provides guidelines for laser power upscale useful in laser microfabrication.

The main objective of this research is to adopt the best knowledge and validate the laser surface texturing technologies for printing/embossing and high throughput surface texturing applications.

For metals, the specific removal rate increases with increasing peak fluence and reaches a maximum value when the peak fluence is at its optimum value and then drops for higher fluences. The surface quality is high at the optimum point with the highest efficiency, but the quality is still acceptable for higher fluences. Using higher pulse energies, therefore, leads to a less efficient process with slightly reduced surface quality.

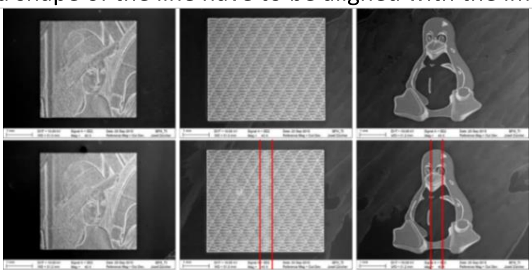
For steel 1.4301 the specific removal rate shows a maximum value at an optimum fluence. At this point, indicated by (1), the surface quality is also high as for copper and nickel. However, for even at slightly higher fluence, the formation of cavities can be observed (2). These cavities begin to form clusters if the fluence is further raised and finally cover the whole surface. That leads to a strongly reduced surface quality and to a further reduction of the specific removal rate.

Thus, the process window concerning the pulse energy or fluence is only very narrow for steel 1.4301 where cavity formation strongly limits the value of the fluence that can be applied. In contrast, it is mainly constrained by the drop in efficiency and is therefore quite wide for copper and nickel. The ablation efficiency increase for steel by power scaling can be done by enlarged spot size on the surface.

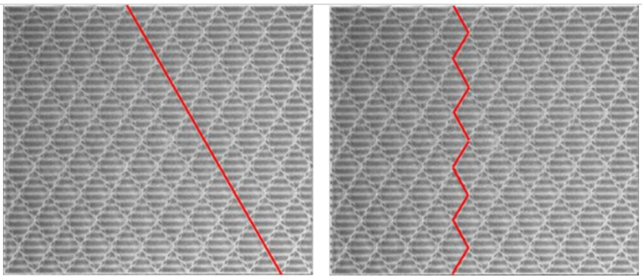


Specific removal rate depending on the peak fluence for steel 1.4301 and microscope pictures of the surface for specific peak fluences indicated with (1) – (4).

The precise stitching of multiple scan fields is crucial for laser micromachining of large surfaces. Three different 3D-structures are marked once without stitching and once using the stitching strategy. Visibility of the intersection area strongly depends on the surface of the 3D-structure itself. The averaging of a stitching line border strategy results in a small line on the surface. This line is clearly seen on the surface but not measurable. To avoid this effect, the position and shape of the line have to be aligned with the image



SEM images for three different 3D-structures; upper row: non-stitched images; lower row: stitched images.



Different solutions to align the averaging line border strategy.

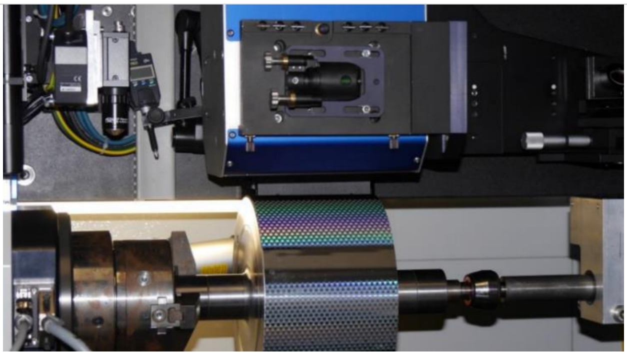
HOW TO EXPLOIT?

The laser micromachining quality can be optimised by the machining strategy, and high accuracies can be achieved by synchronising the motion of the axes with the pulse-train of the laser system. Finding optimal machining parameters is important for increasing of laser-based production efficiencies. Optimal allocation of laser parameters allows reducing energy and material consumption during the production process.

Laser texturing for printing /decorative applications

Partners: IOM, Next Scan Technologies, Ekspla, SWG

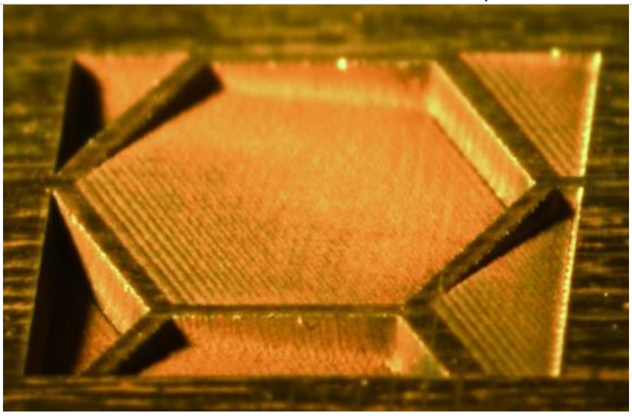
In this section, the results laser engraving and texturing of copper and chromium sleeves are presented. As laser source, the Ekspla Atlantic 60 picosecond laser (60 W, 13 ps, 1 MHz) was used. Next Scan Technology polygon scanner LSE was used as a fast scanning system. The key to Next Scan Technology is its proprietary F-Ω™ strip-mirror optics, combining the telecentricity of F-Theta optics (focal length of 190 mm) with a scan width of 170 mm and proprietary controls SuperSync™ for laser synchronisation. The polygon scanner provides scan speed between 25 to 100 m/s.



Laser workstation with the mounted rotary drive.

The laser processed areas have a high quality, and no very limited post processing of the structured surface are required to fulfil the required quality demands of the most printing and moulding applications. By using specific laser-scanner processing parameter, the generation of self-organized structures can be achieved. The size of these structures can be compared with the length of the used laser light with 1064 nm causing the visual rainbow effect of the laser textured areas. By adjusting the polarisation direction of the laser beam the orientation of the structure can be changed which gives great freedom to generate a variety of visual and functional effects.

The combination of the high-speed polygon scanner system from Next Scan Technology and Atlantic picosecond laser from Ekspla providing high power with high repetition rate have been tested for application suitability. It has been shown that the production of 3D microstructures is possible with the high precision and quality. It has been found that this System is particularly suitable for the manufacture of optically-active, self-organized microstructures not only in the case of quality but also regarding performance and cost effectiveness.

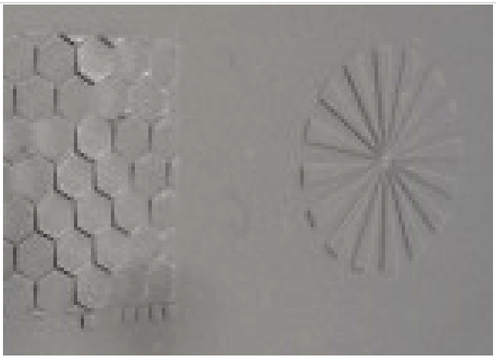


Laser-engraved structure, copper sleeve.

Micrometre size structure with additional optical active nanometre size structures, chromium sleeve.

HOW TO EXPLOIT?

The production of advanced packaging designs, as well as specialised moulding applications, e.g., is an extremely fast-growing market. In order to fulfil the demand of cost, efficient mass production the usage of printing and embossing rolls is a standard technology. Therefore, the fast and flexible engraving of the rotating cylinder is a key element in modern industrial printing and moulding. The usage of laser processing techniques for the engraving process is widely used because of its unique processing characteristic regarding flexibility and processing speed. Laser processing with ultra-short laser pulses gives the possibility for texturing of surfaces with sub-micrometre sized structures by using self-organizing physical effect. Due to the sub-micrometre size, these structures are optically active and give the product designers an unexplored option regarding appearance and functionality.



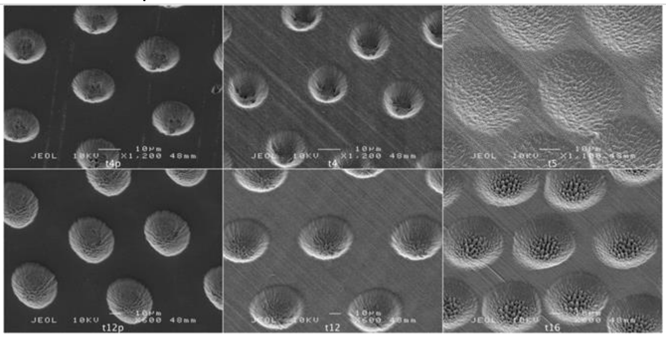
Visual embossing quality of silicone image.

Dedicated nanostructures on moulds for surface functionalization

Partners: Lightmotif, CRF

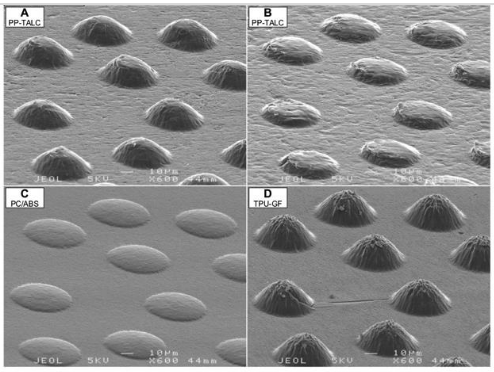
This work is based on a technology previously developed by Lightmotif that enables laser ablation of micro and nanoscale features on 3D curved moulds by ultra-short pulsed lasers. Lightmotif and CRF cooperate with the goal to obtain a method that enables the production of polymer parts for car interiors with added functionality due to a micro- and nano-textured surface, achieved by a textured mould. The surfaces should show a soft-touch effect that results from a largely reduced contact area of skin and polymer part. Besides the haptic properties of the surface other relevant aspects like aesthetic properties of the textures should be optimised.

Percussion drilling of large dimple diameters is limited by the available spot size range and the limited fluence range. When using trepanning approach, it appeared that higher fluences could be utilised for machining dimples compared to percussion drilling. A trepanning diameter of 0.65 times the percussion drilled hole diameter leads to well-shaped dimples with a diameter up to about 40 % larger than that of a percussion drilled dimple. That can be further increased by using trepanning with multiple trepanning circles.

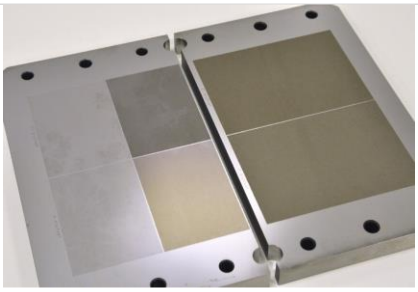


SEM images of dimples produced by trepanning.

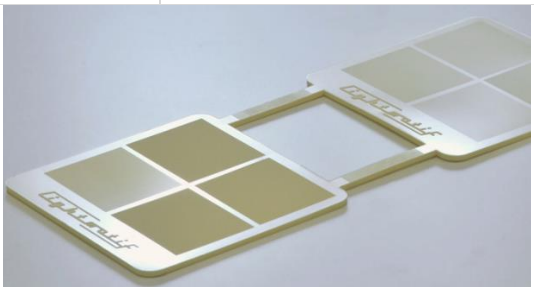
The four selected candidate textures were used to texture mould inserts, using the new dimple-distribution method and laser cleaning. This way, the processes are exactly how they are intended to be used on 3D curved surfaces.
The replication of the four samples (A-D) is presented in the figure below for each of the four textures. The replication fraction is obtained by dividing the measured height of the replicated pillar by the depth of the dimple in the mould. SEM measurements of replicas of texture are presented for each of the four plaques.



SEM images of the dimple replicas of texture 12 in the four test polymers.



Flat mould with the optimised texture.



Plaque injection moulded with laser textured mould.

"Soft-touch" surface.

HOW TO EXPLOIT?

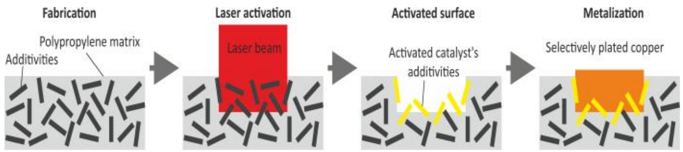
Utilisation of picosecond lasers in texturing of moulds for automotive interior parts offers freedom of designs. This new technology enables texturing of surfaces with features at the micro and nanoscale. Such surfaces can exhibit functional properties like superhydrophobicity, anti-glare, soft-touch and others.
This method is more environmentally friendly compared to traditional mould texturing by etching method as using of hazardous acids is avoided during the process. Using of laser micro-texturing allows mimicking etched surface, for example like the leather imitation textures. This method allows reducing production steps compared to the painting of moulded plastic. Hence it increases production capacity.

New laser activation and chemical deposition concepts

Partners: FTMC, CRF, BioAge

Work on laser structuring of polymers and metal plating was performed by CRF and FTMC, defining suitable regimes of laser structuring. Excellent results were achieved with polypropylene based material. BioAge has worked on the electrical design of touch sensors that will be used to validate the equipment and technology.

The main objective is to design and develop reliable schemes for direct writing of 3D wiring by laser radiation. The approaches focus on new technologies in order to overcome basic problems of the current state of the art and to perform surface processing of standard plastics instead of using highly specialised and expensive.

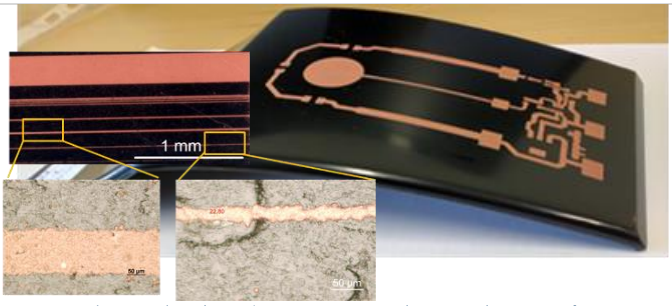


LDS process by steps.

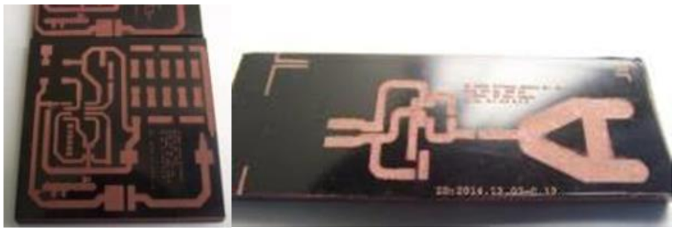
The basic technique of laser writing for selective plating on plastics is Laser Direct Structuring (LDS). In LDS method, special fillers are mixed in the polymer matrix. These fillers are activated during laser writing process and in the next processing step scanned area can be selectively plated with metals, using autocatalytic electroless plating.

New material, polypropylene with carbon-based additives, was tested for LDS approach.

Different laser processing parameters (laser energy, scanning speed, the number of scans, pulse durations, wavelength and overlapping of scanned lines) were applied in order to determine the optimal regime of activation. Selectivity tests showed high spatial plating resolution. The narrowest plated line was less than 23 µm in width. Scanning speed for surface activation was achieved higher than 1 m/s, overcoming a few times the current state of the art.



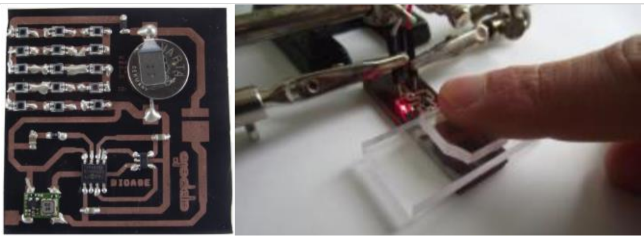
Selectively plated copper on polypropylene surface.



APPOLO sample for contact sensors and temperature sensors.

Specific electronic layouts have been designed by BioAge and CRF and manufactured transferring the layout by the laser on plastic plaques: capacitive touch sensor for automotive glove box cover and temperature sensor for environmental monitoring.

The demonstrators were structured by the laser scribing, and the copper was deposited on them in order to create a conductive track. Their performance is on validation by partners.



Temperature sensor and Capacitive demonstrator tuned in order to have different sensitivities.

HOW TO EXPLOIT?

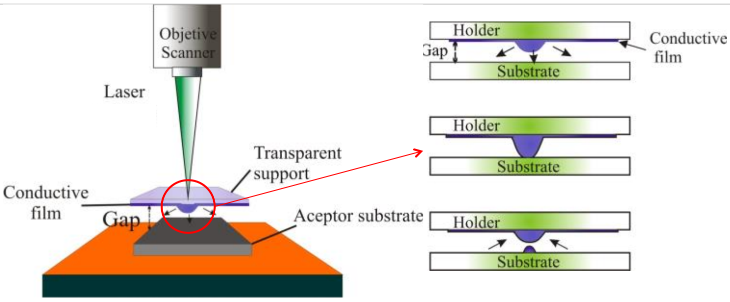
Laser writing for selective plating of conductive lines for electronics has several significant advantages, compared to conventional printed circuit board technology. Firstly, this method is faster and cheaper for prototyping. Secondly, material consumption is reduced, because it works selectively. However, the biggest merit of this approach is potentiality to produce moulded interconnect device, enabling to create electronics in 3D structure, thus saving space, materials and cost of production.

LDS method is attractive for automotive industry because it brings creative freedom for designers. Various plastic parts which include electronic circuits to increase their functionality can be no longer limited by the necessity of incorporation of printed circuit boards. Saving also comes from reduction of wiring in the car. This method allows much lower consumption of material achieving the same functionality as well as reduction of production costs and production steps. Both, laser-induced surface activation and selective electroless metal deposition were advanced in creating Moulded Interconnect Devices (MID).

LIFT process for top contacts in photovoltaics & electronics

Partners: UPM, Ekspla, Onefive, Mondragon Assembly, Abengoa

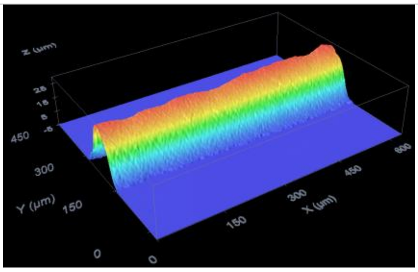
LIFT uses laser pulses to push thin discs of material from a transparent donor substrate and deposit them onto an acceptor substrate. The laser beam is focused on the donor substrate/ribbon interface. Laser energy is deposited within the laser spot size into the interface, evaporating a little amount of the material and generating the expansion of the remaining material, accelerating the non-evaporated part of the metal film towards the acceptor substrate.



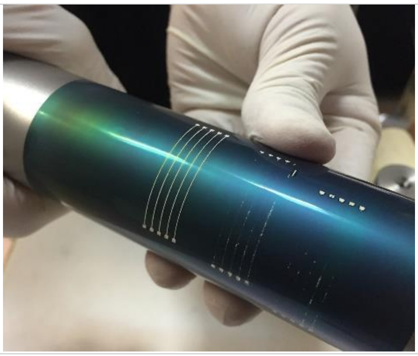
Principle of LIFT process for metallization of thin-film solar cells.

The laser-induced forward transfer (LIFT) process is a technique to transfer various materials onto a number of various substrates.

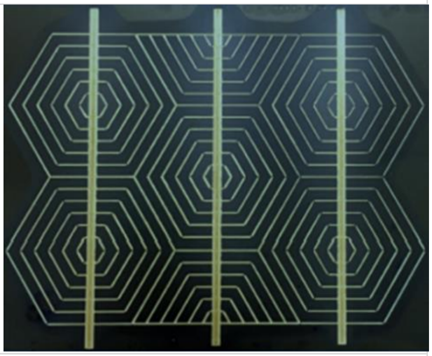
VIS/UV ns/ps-lasers were utilised for metallization onto CIGS substrates, silicon wafer and for metallization in flex 3D microelectronics devices. Different process parameters were used in assessment of laser curing/sintering the silver paste. The goal of the treatment was to obtain the lowest possible resistance of the printed features at the lowest possible temperature to allow the process on flexible polymer substrate or heating the acceptor. A low curing temperature of a metallic ink or paste is necessary for flexible electronic and photovoltaic applications to avoid damaging to the substrate. This effect can be achieved with the laser local heating that prevents heating areas of the substrate where no ink or paste is present. This process had to reduce the electrical resistivity and produced a good electrical conductor for flexible optoelectronic devices keeping the integrity of the line without reducing the adhesion of the silver line to the flexible substrate and without damaging the substrate.



Profile of metal line on CIGS formed by LIFT process.



LIFT printed grid lines on a flexible substrate for photovoltaics.



Crystalline Si solar cell with LIFT printed silver grid.

HOW TO EXPLOIT?

In the ns regime, is difficult to control LIFT of very precise geometries, but using of ultrafast lasers (especially in the UV range) can overcome this difficulty. Relative translation of the source and substrate, or scanning of the laser beam, allows the complex pattern formation in three dimensions in a conformal way. In this work, the idea is to use VIS/UV ns/ps-lasers for metallization onto CIGS substrates and UV/ps lasers for metallization in flex 3D microelectronics devices. The assessment has shown the possibility of doing LIFT printing of silver grid on commercial screen using picosecond-lasers. The assessment has also demonstrated that lines can be done using fix lens, conventional scanner and the high-speed polygon scanner from Next Scan Technologies with the high aspect ratio.

Laser-Induced Forward Transfer (LIFT) process was successfully validated for free-form front contact grid printing with picosecond lasers on silicon solar cells. One of the final milestones is to metallize a whole cell, in order to advance in this task, the full metallization of a front grid has been performed to check if the process is suitable for printing in large areas.

LIFT metallization can be used to print the front grid without the need for a silk screen. That allows the printing of different grids just by changing the program for the scanner giving great process flexibility.

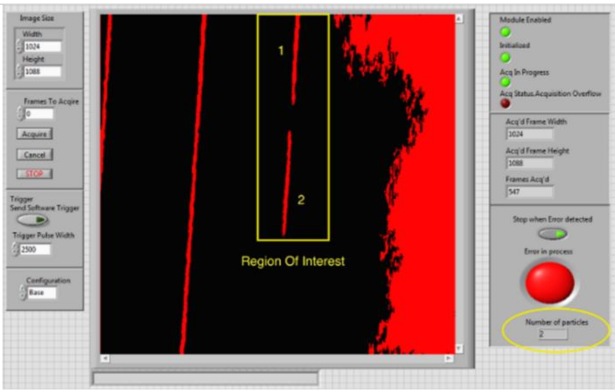
Development of sensing and monitoring techniques for processing and validation

Partners: LUT, AMSYS, ELAS

Laser material processing is a future technology which is easy to control and automate. However, this can be achieved when different sensing and on-line monitoring techniques are implemented together with a laser beam. APPOLO project includes a special Work package for development and validation different on-line monitoring techniques that can be useful for other WPs implementing assessment of new equipment and laser processing processes.

On-line detection of defects during laser scribing. LUT developed the real-time monitoring system based on a high-speed camera and spectrometer. The monitoring tools include a spectrometer, a high-speed camera with an active Cavitar illumination system. With a high-speed camera (max 500 fps), recognition of the defects was achieved at the maximum process speed of 1100 mm/s. This was demonstrated for laser scribing in CIGS, Cr/Glass and Mo/PI.

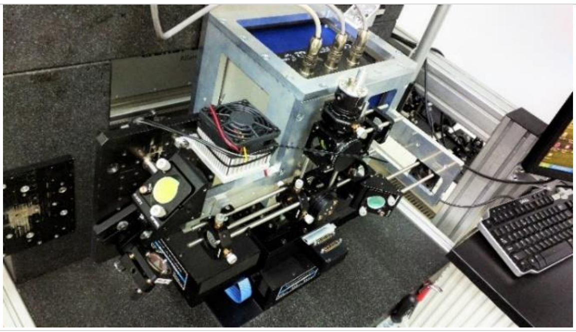
Test bed for the on-line monitoring experiments.

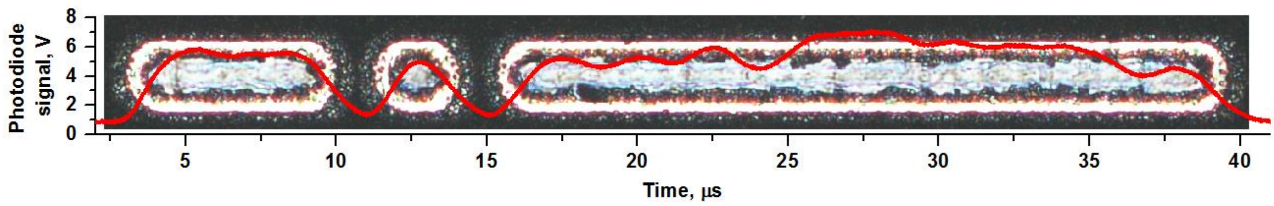


Screen shot of the defect recognition software of LUT.

On-line monitoring of the laser process running at 50 m/s speed through polygon scanner (AMSYS)

New on-line methods were designed and evaluated for the high-speed and precise in-line monitoring of laser scribing processes by utilising polygon scanners. The special optical system was developed to measure the reflection signal from the surface during the laser fabrication process. Such system helps to detect defects in the fabricated profile instantly and perform online monitoring of the laser process.





Microscope image of the P3 scribe made in the CIGS solar cell by direct laser ablation and the photodiode signal measured on-line during the ablation process.

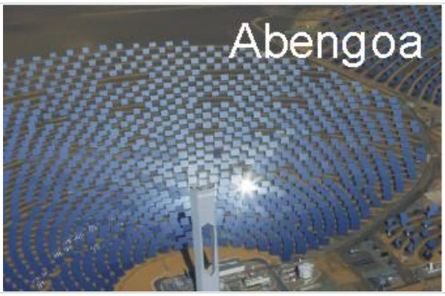
HOW TO EXPLOIT?

Online monitoring systems are crucial for any industrial process. Online defect detection system and on-line monitoring systems enables controlling laser microfabrication processes at high speeds and allows detection/correction of the defects. Such systems increase laser process feasibility and allow to minimise failures during microfabrication process in industrial systems.

Adoption of monitoring systems allows increasing laser technology feasibility and reliability in thin-film scribing for photovoltaics and electronics. It also reduces wasting of production material, increases scribing quality, as post scribing inspections are irrelevant when online monitors systems are used.

Application areas of APPOLO technologies

Photovoltaics

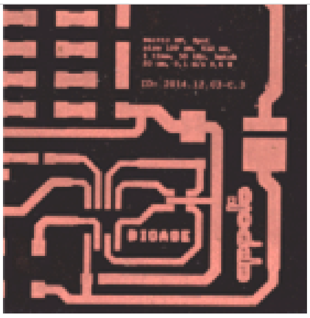


Jewellery

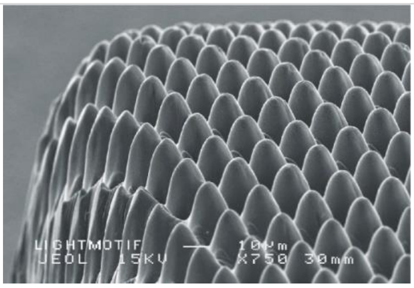
Printing and embossing

Automotive

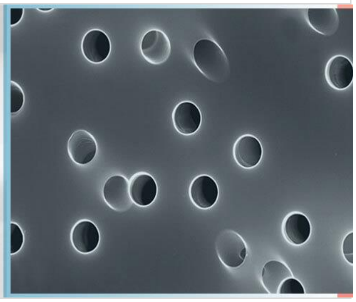
Electronics



Machinery



Bio-medicine



SUMMARY

APPOLO project is filling the gap between lasers producers, system integrators and end-users. APPOLO HUB – network of laser application laboratories deals with this issue working as knowledge transfer organisation providing laser process validation services. During APPOLO project validation of laser processes for thin film photovoltaics, printing/embossing and automotive applications are being developed.

Lasers from Ekspla, Lumentum and Onefive combined with polygon scanners of Next Scan Technologies are powerful tools for various precocious laser micromachining applications.

Validation of new laser sources for photovoltaics industry should fasten laser integration into production processes bringing advantages of ultrashort pulsed lasers microfabrication:

- Debris-free process;
- Flexibility for changing scribe dimension;
- 24/7 operation.

Validation of the laser surface texturing technologies for printing/embossing and high throughput surface texturing applications helps to optimise usage of laser parameters during the production process. Investigation of “stitching” methods allows using laser-based microfabrication for large-area treatment.

Laser texturing of injection moulds allows forming nano/microstructures which provide soft-touch features for plastic automotive parts. Changing of laser texturing parameters allow to vary such properties as glare, hydrophobicity or imitate leather surface. Employing laser in mould modification reduces production steps for automotive parts and offers etching-free process without the use of hazardous chemical reagents.

Laser direct structuring of plastics provides selective plating technology. Electronic circuits can easily be transferred on plastic plaques. This method allows reducing material consumption during production process simultaneously increasing the functionality of plastic parts and providing freedom in design for automotive.

Using ultrafast lasers in LIFT process allows controlling precise geometries bringing them for commercial screen printing of silver for photovoltaics or flexible 3D microelectronics devices.

Sensing and monitoring techniques, developed during APPOLO project, allows controlling laser material processing by the detection of defects during the high-speed laser process. These techniques increase process reliability and ensure quality control.