Publishable Summary

The APPOLO project has established 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 (preferable SMEs: for integration, lasers, beam control and guiding, software, etc.) in order 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 accumulating knowledge and infrastructure and promoting the easy-to-access environment for development and validation of laser-based technologies.

The APPOLO project covered activities on technical, technological and economical assessment of new equipment supplied by project partners in 8 complex assessment value chains and 7 new assessment experiments and developing the standardised procedures for the assessment service with can be provided for new project partners and customers beyond, All activities of the APPOLO project during the fourth year of implementation were performed close to the work plan. Dissemination and exploitation plans were finalised at the end of the fourth year of the project (Y4) reflecting the new knowledge generated in the project.

The HUB network model was finalised during Y4, and the Cooperation Agreement was signed by FTMC, IOM, BUAS, UPM and ENG. Further HUB sustainability steps include seeking HUB partners outside APPOLO consortium. Main HUB customers have chosen as laser technology end-users and laser system integrators, both needing for qualified laser technology-based manufacturing process validation– short tests and long-term trials.

Workpackage ***WP2 "Assessment of the ps-lasers for CIGS solar cell scribing"*** finally was finished with nearly all goals reached. During the implementation period, significant delays were accumulated in particular tasks due to unavailability of the scheduled equipment for assessment.

The LSE300 polygon delivered by NST was thoroughly validated by FTMC in metal ablation and thin-film scribing, showing good performance in both types of processing. Some long-term stability issues still need to be fixed. As an alternative approach in the validation of on-line monitoring techniques developed by LUT, the monitoring techniques were tested in a colour marking of metals and additive manufacturing by selective laser melting paving the way for exploitation the project results.

A set of optimised high throughput scribing processes with the scribing velocities higher than 1 m/s has been developed by BUAS and validated on R&D samples and functional modules on the float glass substrate produced by EMPA. A small batch of functional modules was produced in cooperation with FLISOM to test the in-process performance of the fibre delivered scribing laser. The fibre-delivered ultrashort pulses can be used for thin-film solar cell scribing including the high-throughput P2 process employing specifically tailored spot profiles. It was shown that optimised scribing processes developed in APPOLO are ready to be implemented in industrial scribing machines.

WP3 "Assessment of the ps-laser based CIGS solar cell scribing technology" was finalised with a renewed goal on perovskite thin film solar cells with manufacturing the first all-laser-scribed

mini-modules. It was shown, that perovskites films can be ablated at very low fluences by almost any ultra-short pulse laser system. The main thin film removal mechanisms are laser ablation and thin film delamination lift-off. Material modifications can be found only for ns-laser sources due to the decomposition of the perovskites to PbI_2.

For the application of the laser scribing to mini-modules fabrication a solar cell design was developed that will allow finally semi-transparent modules developments. Both the front and the back electrode made by TCO films. This design, however, is much more challenging for all-laser scribed integrated module fabrication. All-laser scribed integrated-interconnected mini-modules were fabricated on rigid and flexible substrates, meaning glass and plastics. The fabricated modules were fully characterised by electrical measurements proving a champion module efficiency of 10.7 %.

The potential application of perovskites is flexible tandem solar modules with a CIGS bottom module. The expected higher efficiencies of tandem modules enable savings of the total cost of PV systems due to the reduced area of the installations.

Activities in ***WP4 "High-speed surface texturing by lasers"*** were affected by many delays in delivery of equipment during the whole project period. Limited average power of Lumentum laser and remaining issues with LSE170HNA polygon did not allow to reach the final goals as planned. However, the results of the engraving and embossing tests utilising laser-textured sleeves show high-quality surface structures, which cannot be reached by conventional methods. The details of fine structures are precisely reproduced without missing elements down to the resolution of 1000 l/cm. Due to the significantly improved depth resolution without observable steps, the developed technology and set-up should be tested in the field of optical embossing structures as, e.g. Fresnel lenses or lenticular. With an additional improvement in the resolution, even applications in the security filed could be targeted.

The replication process was easy to perform because of the surface properties of the ps-laser engraved copper structure shows the good release of the foils or silicone mass without destruction of the foil, unwanted residuals or failures. However, the speed of the engraving still needs to be improved to obtain more attractive values for industrial use. Utilised a higher average power laser and all benefits of improved polygon scanner, the machining time could be reduced by a factor of 4.5.

The objective for the last year in ***WP5 "Surface functionalization by laser texturing"*** was to assess if the new 1 ps laser developed by Lumentum improves the dimple machining process. This task was already delayed due to the late delivery and problems with the Lumentum laser source. Finally, the partners decided to use another laser which offers the same short pulse length of 1 ps and which was available at BUAS. BUAS started these experiments at the end of the third period and finished them in the fourth period. For every pulse duration (325 fs; 1 ps; 10 ps), the ripple formation was observed, melting effects increased with the pulse duration, and no difference was observed in the dimple bottom roughness.

WP6 "Laser direct writing for flexible/3D electronics", *WP7 "Laser direct writing for flexible electronics and photovoltaics"* and *WP8 "On-line monitoring tools for laser-based technology assessment"* were fully finished in previous years, and no more direct activities were performed

in Y4. FTMC, CRF, BIOAGE continued activities of WP6 on the further development of the SSAIL technology to higher technology readiness level, looking on new funding options and necessary partners according to whole manufacturing value chain.

WP11 "Implementation of assessment selected via competitive call" covered all activities in seven new equipment assessment experiments. Disturbance with the late start of the new experiments continued all the time. Nevertheless, most of them reached the final goals.

In the ***FAST*** *(Fast and accurate scanning systems for micro-milling of low friction surface textures)* experiment, an improved scanning system of SCANLAB was assessed by LM, and new processes are developed for the fabrication of functional surface textures that SKF wants to use to reduce friction in their products. The fast pixel mode was implemented by SCANLAB allowing control of laser operation at a synchronised repetition rate up to 3.2 MHz. The precise laser patterning speed was increased up to 2 m/s with a high material removal rate and applied in surface texturing of moulds. The processing time for a demonstrator insert with a total volume to be removed of 11.5 mm^3 was around 30 minutes when using a process with an average laser power of 5 W.

The ***PONT*** *(Polymer NIR Laser Resonance Texturing)* experiment aimed at evaluating the performances of a resonant near-infrared ablation in the spectral range of 1500-2000 nm. The laser technology was considered to drill holes in polymer films. The Resonant IR laser ablation was tested utilising sub-ns and ps- OPO laser systems delivered by LASERSPEC. Extended study at FTMC and OSAI provided a comparison of the Resonant IR and UV laser ablation of polymers, in particular toward requirements of the end user IT4IP. The RIR approach leads to significant thermal impact to the material, and the ablation threshold is tens time higher compared with that of UV (355 nm) radiation. The experiments confirmed necessity to use ultrashort (ps, fs) laser pulses, preferable to UV, to avoid excessive heating of the remaining polymer during the processing.

Within the ***LADRUM*** *(Laser patterning of DRUM-moulds for large area nano-imprinted polymer foils)* experiment, the whole process of the pattern design, fabrication steps and techniques for characterisation were developed and implemented for roll-to-roll UV nanoimprint lithography (R2R-UV-NIL). Many efforts was put in laser fabrication of hierarchical structures on drums combing patterning with 1064 and 355 nm radiation at IOM and validating their replications. The selected patterns were successfully transferred on seamless nickel sleeve. A fabrication chain for the fabrication of micro/nano-textured web materials comprising of laser direct surface texturing and UV-NIL replication allows high throughput large area patterning of flexible web materials without a seam and with high precision. The goal of producing functional films with tailored wetting properties was demonstrated by NANOTYPOS featuring surfaces with water contact angle values of up to 158°.

A fibre delivery of pulsed laser radiation using Kagome type fibre was prepared by OPI and validated in the ***NEW-DELI*** *(A new fibre-based delivery system for pulsed laser beams)* experiment by BUAS and IRIS. Performance and stability were tested at BUAS with fibre lasers from ONEFIVE. Real testing of the fibre delivery was performed in experiments on laser scribing of thin-film solar cells with picosecond lasers. NEW-DELI cable has been tested at 10 ns with 20 kW peak power; 150 ns 1 mJ pulses and 10 ps 300 mJ pulses. M2 factor smaller than 1.2 has resulted in a coupling efficiency of around 85-90%. No fibre damage has occurred when operating with ultrashort lasers.

The ***FASTGalvo*** *(Ultra-fast galvoscanners for laser micromachining)* experiment combined the developments of SCANLAB and BUAS to ramp speed of laser processing utilising galvoscanners.

Precise processing of small features is now feasible at a speed of 15 m/s utilising a new excelliSCAN scanner, RTC6 control board and advanced control from BUAS. The performed experiments showed that the newly developed scanner technology allows to take benefit of increased acceleration values and marking speeds in all applications. Significant reduction in the overall machining time has been observed at maintained or even improved machining quality. For some applications, this scanner technology even allowed to use the laser system up to its limits. Therefore, it is very well suited for most micro-machining applications with minimal machining times. Bidirectional scanning, as well as the adaption of the scan line length to the bitmap proposed by BUAS, should be implemented. The technologies were validated by BOSCH in the fabrication of small structures and reopening holes for cooling by GE.

The main objective of the ***DECOUL-Cr*** *(New Ultrafast Laser equipment for DECOrative finishing in automotive Chrome plated parts)* experiment was to study the use of pulsed laser sources to induce changes in chromium-coated parts. Two different laser sources have been applied by UPM, and different effects were observed on the marked areas of MAIER chromium-coated plates. The surface finishing utilising LIPSS offers a new exciting aesthetic that could be applied to chrome parts. A comprehensive assessment of picosecond laser equipment for decorative marking of the chromed part has been done. The experiment reached its final goal providing a validated technology for automotive industry. At the same time, LASING developed the whole laser processing system implementing the technology ready to be integrated into a manufacturing line.

A modified sub-nanosecond high pulse energy laser from SISMA was investigated at FTMC and validated in the deep engraving of metals for jewellery in the ***SUN-JELL*** *(Novel sub-ns laser system assessment for jewellery and luxury fine marking and engraving applications)* experiment. Delays in delivery and discovered problems with laser performance did not allow to reach the final goal. However, the performance of a new laser was tested in the SISMA laser machine as well. Use of sub-nanosecond pulses in delicate marking of metals have shown promising results to continue. A water-assisted laser ablation helped to prevent surface oxidation and debris formation. The materials ablation rates reached 0.005-0.021 mm^3/s, while surface roughness was below 2 µm at a laser power level of 12 W. The SUN-JELL laser source was integrated into a SISMA laser machine, and their performance was validated in deep engraving stainless steel, brass and gold for the end user LAC.

In the fourth year, the exploitation and dissemination strategies of the whole APPOLO project and every consortium partner were updated. Internal RTD activities have progressed significantly, and the opportunities for exploitation after four years of project implementation became more clear and specific. Dissemination activities show good results, mainly due to the strong partners' representation of the APPOLO project at many international events promoting the project results and the APPOLO HUB idea. Two new issues of the APPOLO newsletter and a brochure were prepared and distributed. The dissemination activities were coordinated with the I4MS initiative. Two websites are running for the project: www.appolo-fp7.eu for all project related activities and dissemination and http://appolohub.appolo-fp7.eu/ for APPOLO HUB as a single access point to consolidated infrastructure and expertise of the laser application laboratories, involved in the project. Amount of public information was significantly enlarged on the website.

Further steps were taken to collect all IP and exploit it accordingly strategically. Twelve applications for patents are submitted or are in the process of submitting out of 37 innovations in total generated in different workpackages. Partners expect to be able to generate sales of € 76M

over the next 5 years with these innovations, generating at least 66 additional jobs with this. Long discussions led to a HUB sustainability strategy promising to keep the APPOLO HUB in place as both a cooperation and a marketing & sales tool and the Cooperation agreement was signed among regular partners.