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 cover 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 third year of implementation were performed close to the workplan. Dissemination and exploitation plans were updated at the end of the third year of the project (Y3) reflecting the new knowledge generated in the project.

The HUB network model was established during Y3. The HUB is aimed to make a research-oriented network, where industrial partners will come to test, assess and implement novel laser solutions for their markets. The HUB members actively promote their activities as to showcase their achievements in laser processing solutions. The output of the assessment made possible industry demonstrations of laser applications in their particular field. The APPOLO HUB role, therefore, is to assess these applications in the research framework, allowing all industrial partners to develop successful applications for manufacturing use.

After a long search of proper forms to present annual APPOLO results, the public brochure reviewing achievements in the first half of the project was prepared in April 2016. The main achievements of APPOLO partners were presented in other forms during conferences, EC events and exhibitions. Public presentations of some results were postponed due to patent applications.

Activities in **WP2** were not finalised during the planned 36 months period. During the implementation period, significant delays were accumulated in particular tasks due to unavailability of the scheduled equipment for assessment. The on-line monitoring tools from LUT and AMSYS were validated in laser scribing experiments at FTMC enabling control of the process with a scanning speed of above 1 m/s and recognise defects in the ablation trench less than 50 µm at the scan speed of 50 m/s through optics of the polygon scanner LSE170. ELAS has finished upgrading their laser processing system and finalised integration of an embedded Roll-to-Roll unit to the DuoMaster laser system at FTMC for validation of the laser scribing processes of CIGS solar cells on flexible polymer foils. Fundamental harmonics of the 1.34 µm picosecond laser from Ekspla was utilised with promising results in the P2 and P3 processes on CIGS and CZTSe thin-film solar cells. The final WP2 assessment at FTMC can be done, when LSE300 polygon will be delivered by Next Scan Technologies.

Development of laser systems was ongoing at Onefive in Y3. The 100 W operation was achieved at the 400 kHz pulse repetition rate. However, the fibre laser system will not reach a product level within the duration of the APPOLO project. Therefore, an assessment as a laser source alone or in the scribing process is postponed.

A set of optimised high throughput scribing processes with the scribing velocities higher than 1 m/s has been developed and validated on R&D samples and functional modules on the float

glass substrate produced by EMPA. Due to temporal problems with the sample production, scribing machine and laser source, the alternative workflow for industrial assessment experiments was proposed. A significant part of the planned assessment experiments can be carried out, given that the RTD work in WP2 will be continued for a limited time.

Scientific paper “CIGS thin-film solar module processing: the case of high-speed laser scribing” reviewing all achievements in high-performance CIGS solar cell scribing with ps-laser, combining input from FTMC, BUAS, EMPA, and NST is submitted to Scientific Reports journal.

Due to the modification of **WP3**, the focus was moved from CIGS to perovskite thin-film absorbers. This promising material drives the developments of recent boosting photovoltaic market. Based on this knowledge a mini-module design including an adapted fabrication process for the realisation of all laser-scribed perovskite mini-modules was developed by the collaboration of IOM with EMPA. To ensure a safe and low-damage handling of the samples to get reliable results regarding the laser scribing a common protocol of best practice for handling, processing and storage of these perovskite samples was developed and implemented.

For all laser scribes, a speed more 1 m/s was achieved with the reference lasers. That high laser scribing speeds together with the deposition techniques enable a low-cost fabrication of all-laser-scribed modules. The full aperture module efficiency of the first generation all-laser scribed perovskite solar cell exceeds already 10% and reinforces the chosen approaches of thin-film fabrication and laser scribing. The obtained results are the basis for minimising serial resistance and dead area losses of the interconnection area for further module efficiency improvements. All important goals, milestones and deliverables were achieved in this period.

Year 3 of **WP4** was affected by **delays in delivery of equipment.** The transfer of a 100 W laser into an industrially-suited prototype has led to unforeseen problems which limited the output power. The development of the new high-NA version of polygon scanner faced some problems with reflecting f-theta optics. Nevertheless, Y3 was used to finish optimisation and stitching experiments as well as for the preparation of the set-up and its control. It was shown that for copper and brass a power scale-up into the 300 W regime with 3 ps pulses is possible and the removal rate in the range of 1 mm^3/s can be achieved. For steel, the heat accumulation is limiting the power scale up, and alternative approaches have to be developed to deal with 100 W average power or more. WP4 needs to be extended until the end of the APPOLO project, and the real results will depend on availability the proposed equipment.

In **WP5**, a 3D mould texturing method was assessed and optimised for applications on automotive interior components, with the goal to obtain soft-touch effects by the micro/ nano-textured surfaces. Optimisations of the textures and the laser process were performed. They were supported by experiments on produced parts and generated a feedback for the optimisation iterations. The new textures offer innovative surfaces where glare and haptic properties can be tuned, which is not possible by conventional textures by (laser) engraving. Depending on the used polymers, the costs can be comparable to that of conventional processes. The visual appearance of the surfaces was improved step-by-step and finally resulted in a perfectly homogeneous surface texture, enabled by a random dimple distribution on the surface. The necessary increase in cycle time is very dependent on the used polymer, as this largely determines the increased difficulty of texture replication, and therefore needed mould temperature.

The requirements for automotive applications are very tough and could not be completely met in the performed experiments. Especially the wear resistance of the textured polymer surfaces was not sufficient. That can be considerably improved by further optimising the material choice. For applications outside the automotive sector, the example includes minimising skin irritation for healthcare products and increased user comfort for consumer products. That shows that although for automotive applications further optimisation is needed, the developments within APPOLO have resulted in the technology that already is gaining acceptance by the industry.

All targets of **WP6** were achieved, manufacturing demonstrators in two main sectors as automotive and sensor. All the selective plated samples have been successfully assembled to manufacture the two expected final demonstrators as automotive glove box and temperature sensor. The comparative cost analysis shows clear benefits of the technologies developed in APPOLO during the assessment of lasers for selective electroless metallization. Initial approach coming from CRF of the use polymers with carbon additives allows reducing the metallization related cost about two times comparing with the conventional LDS technology, using metal additives. The notable better performance was found in the new SSAIL technology, where polymers without additives are used, but only picosecond lasers can give the required polymer surface excitation. Two patent applications were submitted by FTMC for those technologies and various approaches for faster their commercialization are now discussed between partners.

The main objective of **WP7** was to adapt the Laser Induced Forward Techniques (LIFT) for metallic contacts on flexible optoelectronics devices. In this third year of APPOLO project, it has been proved that laser curing and sintering of silver paste lines printed using LIFT can be achieved, but there is a small parametric window for obtaining the desired properties, making it a very sensitive process. As a proof of concept, the full metallization of a CIGS solar cell on steel flex substrate with fingers and busses deposited by the proposed LIFT technology has been performed and its electrical properties have been measured. The assessment has shown the possibility of metallizing a CIGS solar cell using LIFT and obtaining a working solar cell. Mondragon Assembly has successfully built and installed the required set-up for adhesive dispensing, LIFT and curing processes assessment at UPM. Mondragon Assembly is now in the position for offering turn-key dispensing machines, already assessed for adhesives/pastes dispensing, as well as for curing processes.

WP11 covered all activities in 7 new equipment assessment experiments. Due to the late legal accession of new partners, start on those new experiments was not smooth and equal.

In the **FAST experiment**, an improved scanning system of SCANLAB is 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 higher scanning speed with faster laser gating control should help to manage heat accumulation leading to surface melting.

The **PONT** experiment aims at evaluating the performances of a resonant near-infrared ablation in the spectral range of 1500-2000 nm. The laser technology is considered to perform holes in polymer films and thin layer shaped devices using two new sub-nanosecond laser sources with tuneable wavelength. Initial experiments with available laser sources in mid-IR evident the need of ultrashort (ps, fs) pulses to avoid extensive heating of the material.

Within the **LADRUM** experiment, the whole process of the pattern design, the fabrication steps and the techniques for characterization were developed and implemented. A uniform platform was chosen and applied to a specific sleeve design for that the laser patterning equipment as well as the roll to roll ultraviolet light assisted nanoimprint lithography (R2R UV-NIL) machine has been adapted. First sleeves have been machined for the development of a roll to roll (R2R) process for thin foils, and the seamless replication using the laser-patterned sleeves has been shown.

Identification of the laser process requirements resulting from the existing industrial applications was done in the **NEW-DELI** experiment and based on the industrial process requirements, the delivery system specification have been identified. A first alpha sample has been realised by OPI and tested at own facilities with a nanosecond laser source. A detailed analysis was performed, and a new version of the cable (beta sample) was designed and realised, which assessment will be carried out in the following months.

FASTGALVO started with a delay, and an adaption of the project plan was done. In preparation of the planned experiments, the configurations of the scanner systems to be delivered were discussed with the partners. SCANLAB also analyses alternative scanner system configurations with higher scan speed.

The main objective of the **DECOUL-Cr** experiment is to study the use of pulsed laser sources to induce changes in chromium-coated parts. Two different laser sources have been applied, and different effects were observed on the marked areas of MAIER chromium-coated plates. The surface finishing utilising LIPSS offers a new interesting aesthetic that could be applied over chrome parts.

Laser developments at SISMA are ongoing in the **SUN-JEL** experiment. At the same time, FTMC started metal ablation experiments on samples provided by SISMA using a laser with close parameters, available in the laboratory. The procedures for a new laser assessment in metal ablation are prepared based on the experimental results.

Dissemination activities show good results, mainly due to the partners' strong representation of APPOLO at many international events promoting 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.

Further steps were taken to collect all IP and exploit it accordingly strategically. Five applications for patents are submitted to the date. 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.