Executive Summary:

The aim of the ALPINE project it to push forward the research and development of fiber laser systems for scribing of PhotoVoltaic (PV) modules. The project consortium focused on a new high brilliance, high efficiency and premium beam quality laser based on photonic crystal fibers (PCFs). The all-around development cycle comprising of the beam source, beam delivery and manipulation, scribing processes, PV module validation have been demonstrated. The novel laser systems have been designed to fit the requirements for scribing innovative and flexible PV modules rather than standard ones based on crystalline silicon wafer. In particular, the two most appealing technological alternatives have been considered, that is CdTe and CIS technology of thin-film solar cells. Validation of the quality process has been successfully assessed. The project joined together the two exciting challenges of the laser development for advanced industrial processing, on one side, and solar energy exploitation, on the other side. Thus has constitutes a crucial opportunity to continue the innovation of European industries involved in material processing applications by employing laser technology and to consolidate PV manufacturing European position. New promising scientific and technological approaches have been investigated thus stimulating the continuous growth of the market in these strategic fields for European development.

Project Context and Objectives:

The aim of the ALPINE project it to push forward the research and development of fiber laser systems for scribing of PhotoVoltaic (PV) modules. The project consortium focuses on a new high efficiency laser based on Photonic Crystal Fibers (PCFs). The consortium intends to demonstrate the all-around development cycle comprising of the beam source, amplification stage, beam delivery and manipulation, scribing processes, advanced diagnostic and validation of modules. In addition the novel laser system must be designed to fit the requirements for scribing innovative and flexible PV modules rather than standard ones based on crystalline silicon wafer. In particular the two most appealing technological alternatives are considered, that is cadmium telluride (CdTe) and copper indium diselenide (CIS) or copper indium gallium diselenide (CIGS) technology of thin-film solar cells. Validation of the quality production process must be assessed as well.

The project joins together two exciting challenges, the laser development for advanced industrial processing, on one side, and solar energy exploitation through new materials, on the other side. Thus it constitutes a crucial opportunity to continue the innovation of European industries involved in material processing applications by employing laser technology and to consolidate PV manufacturing European position.

To achieve these aims the Alpine consortium focuses on different targets, ranging from the laser development to the definition of new fabrication processes for PV modules, from the integration of PCF technology to the definition of validation protocol of solar modules, and many others. In particular, the work-packages 1, 2 and 3 are in charge for the laser prototype development, based on the new seed and pump laser diodes and on specifically designed PCFs.

The fourth work-package is devoted to the production of new PV module on flexible substrates using different production technologies, such close-spaced sublimation, thermal deposition, thermal co-evaporation, electro-deposition. The work-packages 5 and 6 constitute a sort of contact point of the two previous activities, being in charge to integrate the laser prototype in an industrial scribing machine and to perform the scribing tests on the provided PV modules. Work-package 7 validates the scribed thin film modules, both in substrate and superstrate configuration, for both CdTe and CIS, benchmarking results to the state of the art module production.

In order to achieve these results the consortium has defined specific objectives specifically listed in the following for each WP.

WP1

- Development of MOPA prototype operating at 1064 nm.
- Development of a new and cheap photo-elastic electro-optical modulator.
- Perform an amplification numerical analysis in large mode area PCFs.
- Assembling the MOPA and Q-switched lasers with a high power rod type amplifier.

WP2

- Development of a seed narrow linewidth DFB laser diode in LF package.
- Design and development of pump laser module with dichroic pump protection.
- Development of a seed narrow linewidth DFB laser diode in high-frequency modulation compatible package.

WP3

- Design and fabrication of PCFs to be applied in laser development.
- Production of fiber-optical adaptor and splicing to flexible active LMA fiber and to conventional fiber.
- Realization of PCF splicing to conventional fiber for signal input.
- Numerical simulation of bending performance of active LMA PCFs.
- Development of modelling tools for numerical simulation of active LMA PCFs, where stress induced birefringence effects are incorporated.

WP4

- Realization of a CdTe/CdS thin film solar cell in the superstrate and substrate configuration by close-spaced sublimation.
- Realization of a new process, based on innovative intermetallic precursors, to obtain a highly efficient CuInGa(S,Se)2/CdS solar cell on flexible substrates, by both co-evaporation and electro-deposition procedures.

WP5

- Development of the scribing machine prototype.
- Beam shape and optics integration, control and system software development.
- Scribing tests.

WP6

- Definition of standards for integration of laser in automatic working machine.

- Laser beam moving system.
- Laser beam focusing system.

WP7

- Identification of the requirements for laser scribing cuts of different thin film PV technologies.
- Verification of analytical methods on state of the art material for benchmark with conventional processing.

WP8

- Definition and implementation of dissemination activities.
- Definition of exploitable results.

Project Results:

This section provides, for each work-package, a description of the main scientific and technological results achieved by the project.

1. WP1: Design, development and optimization of fibre laser prototype
Objectives
The goal of this WP is to design and develop an optimized PCF based laser source for cost effective, high quality and fast processing of solar cells. The work is split in two directions: first we defined the best parameters for optimum solar cell processing. This step involves designing and prototyping of a versatile MOPA high power laser module working in the IR, green, and UV. The MOPA device has been adjusted in terms of pulse duration and repetition rate in order to be a powerful developing tool for the solar cell process optimization. In a second step, the results achieved in WP5 with the MOPA prototype have been used to specify and develop a high power Q-switched laser with parameter close to the optimum. This ended up with a cost effective high power fiber laser giving the best process performances.
The partners involved in WP1 are MULTITEL (WP-Leader), UNIVERSITY OF PARMA, OCLARO, EOLITE, LPKF, QUANTA, and UNIVERSITY OF LJUBLJANA.

Summary of progress towards objectives and details for each task

Task WP1.1: Development of MOPA prototypes (100%)
Two MOPA lasers based on a gain switched diode were built by MULTITEL for tests. An additional laser based on a mode-lock source and pulse picking, operating at 500 ps, down to 100 kHz has been done.

Task WP1.2: MOPA assembling and frequency conversion (100%)
The laser from MULTITEL has been delivered to EOLITE for amplification tests. With the EOLITE amplifier it was possible to obtain 8 W at 300ps and 20 W for pulses between 1 and 10 ns. The laser and amplifier were sent together to LPKF for the tests in WP5. Frequency

doubling has been tested by LPKF with another shorter pulsed commercial laser available. Implementation with the MOPA laser from ALPINE has been successfully done as well.

Task WP1.3: PCF high power MOPA (100 %)

The task consists in the optimization of the MOPA structures and test of PCF for all fibred amplification.

1. A laser from MULTITEL combined with the ROD amplifier from EOLITE, whose fibre has been produced by NKT, has been assembled.
2. The ROD solution has been used to make the solar cell scribing.
3. Tests with the flexible PCF have been done in the hundreds of picoseconds regime. The flexible fibers can reach less peak power than the ROD due to non-linearity. Flexible fibers offers a more rugged laser architecture, as e.g. all-fiber solutions. Flexible fibers is an option for processes where less output power or larger repetition rate are needed.

Task WP1.4: New approach of Q-switching (100 %)

A SCPEM device and the relative driver have been developed successfully by UNILJ. The device exhibits a short response time that makes it a good candidate for Q-switching.

Task WP1.5: Q-switch optimization for SCPEM (100%)

Two devices from UNILJ were tested together with EOLITE in a Q-switch laser cavity. The results that have been obtained are the following: pulse duration of 26 ns, repetition rates of 183 or 274 kHz and average output power 47 or 67 W respectively, depending on the used device.

Task WP1.6: High power Q-switch with frequency conversion (100 %)

EOLITE has developed a Q-switched high power laser that can work in the IR, Green and UV. This is the first Q-switched fiber laser in the UV. The performances are

Wavelength: 343 nm

Average power: > 15 W

Pulse duration < 12 ns

Maximum energy: 150 µJ

Repetition rate: 20 -250 kHz

Beam quality: M2 < 1.3

The consortium has done extensive tests on lifetime of the components and particularly of UV optics and crystal. EOLITE has demonstrated over 250 h at 23 W average power in the UV. A green and IR version of the Q-switched laser has been delivered to the UniPR for scribing tests.

Significant results

The prototype from QUANTA operates in the nanosecond regime from 10ns to few microseconds or more. They have been amplified to a few Watts and done with a linearly polarized output.

The laser from MULTITEL operates in a shorter pulse duration regime (300ps to 12ns) and, combined with the amplification module from EOLITE, delivers 8W to 20W (depending on the pulse duration) at a repetition rate of 500 kHz.
The mode-locked laser with integrated pulse picker works with the following specs:
Pulse duration: 500 ps
Repetition rate adjustable 60 kHz to 35 MHz.
Output beam: 1.6 mm diameter collimated and isolated.
Wavelength 1.030 µm.
Linearly polarized.
Size: 60*50/20 cm^3
Output power: 200 mW @ 60kHz and 400 mW for 100 kHz.
These are limit values that we decided to respect to avoid any risk of damaging but the laser could work at higher power. It will be for the operator to take care not going beyond those limits. It is explained in the manual of operation.

Rod amplification and SHG tests have been performed: amplification tests (at 60 kHz) with a 50 µm core diameter rod-type fibre have been successfully performed.
The maximum output power was 6,86 W (with Raman effects appearing) for 50 W pump power. At 100 kHz we reached 9 W and we tested SHG with a LBO crystal. We got 42% conversion to the green. At 300 kHz we had 13 W after amplification.

Explain the reasons for deviations from Annex I and their impact on other tasks as well as on available resources and planning
The only deviation from Annex 1 is related to the integration of a flexible PCF in the amplified picoseconds laser system. The reason for this deviation comes from the fact that the energy and peak power required for the solar cells micromachining is too high for the flexible PCFs. On the other hand, the results obtained with the ROD type amplifier are well satisfactory for the project.
In addition, MULT, SSE and UniPR contributed to scribing test activity. This action was not originally planned for these partners and was proposed to catch up delay in scribing tests. For this aim, MULT used also an in-house available system at 250 ps while SSE and UniPR used a fiber laser prototype developed by UNIPR and Quanta and a green/IR version of the Q-switched fiber laser developed by EOLITE.

Explain the reasons for failing to achieve critical objectives and/or not being on schedule and explain the impact on other tasks as well as on available resources and planning
No objectives have been failed.

A statement on the use of resources, in particular highlighting and explaining deviations between actual and planned person-months per work package and per beneficiary in Annex 1 (Description of Work)
A funding reallocation has been proposed and accepted by the Commission for taking into account the corrective actions for catching up the original planning about laser scribing tests.

2. WP2: Development of active optical components

Objectives

The purpose of this work package was developing active optical components, such as seed and pump lasers, for fiber based laser source. For cost efficiency and also for possibility of applying high speed modulation, the seed lasers were based on a distributed feed-back (DFB) 1064 nm laser diode. The DFB laser diode design is best tailored for the narrow linewidth, low noise, and short pulse operation required for seeding of high power fiber lasers and for frequency conversion. We designed, developed, and manufactured a narrow linewidth seed laser module with 10xx nm DFB laser diode. The seed laser modules were characterized and optimized for high frequency operation. Additionally, multi-mode pump laser modules were adapted to include a dichroic filter in order to provide protection against fiber laser radiation traveling in the backward direction. Partners involved in WP2 are: OCLARO (WP-Leader), University of PARMA, MULTITEL, QUANTA, EOLITE, LPKF, and University of Ljubljana

Summary of progress towards objectives and details for each task

During the duration of Alpine project we:

1. Successfully developed the building blocks of the manufacturing process for the DFB laser diodes (such as grating lithography, etching, and overgrowth).
2. Designed and manufactured highly efficient DFB lasers operating in 10xx nm spectral region.
3. Optimized DFB lasers for high frequency direct modulation.
4. Carried out optimization of module package assembly for HF operation of DFB laser diodes.
5. Built laser module prototypes with narrow stripe DFB lasers and single mode polarization maintaining fiber pigtails. CW operating powers of more than 200 mW at 400 mA out of the fiber is achieved.
6. Performed final test of seed laser modules optimized for ns pulse modulation using fast pulse driver at MULTITEL. Modulation of the DFB laser modules with subnanosecond pulses was demonstrated. The output spectrum modulated with the short pulses exhibited wavelength stabilization even for such short pulses.
7. Developed single emitter multimode 976 nm pump modules with dichroic pump protection against backreflected fiber laser emission at 1060 nm. The protection is realized by applying the dielectric coating to one of the discrete optical elements inside the module, which are coupling the light into the multimode fiber. We achieved ~40 dB suppression for 1060 nm radiation.
8. Built several prototypes of single emitter 976 nm pump modules with dichroic pump protection.
9. The prototypes of both DFB seed lasers and pump modules were delivered to the project partners developing the fiber lasers (University of PARMA, MULTITEL, QUANTA, EOLITE, and University of Ljubljana)

Task WP2.1: Device design of the DFB laser diode structure and development of manufacturing processes (Months: 1-6). (100%)

One of the activities was designing the single mode DFB lasers. Bragg gratings were intended for the emission wavelength of 1064 nm. For manufacturing the DFB laser at least 2 steps of epitaxy are necessary. During the first step so called laser "bottom" epi-structure is grown, which is based on Oclaro's high-power single mode InGaAs/AlGaAs SQW laser diodes. Then the DFB grating should be defined and finally overgrown during the second epitaxial step.
At this stage of the project we considered both first and second order gratings defined using either e-beam or holographic lithography correspondingly. Gratings were etched using the Reactive Ion Etching (RIE) kit. The overgrowth step was optimized in order to preserve the gratings and at the same time to produce good structural quality material.
The narrow stripe ridges were later processed using the standard process well established for Oclaro's narrow stripe laser products.

Task WP2.2: Manufacturing and testing of the DFB laser diodes and packaging of LF modules (Months: 6-12). (100%)

D2.1: Report on the CW performance of a DFB seed laser and delivery of initial samples in non-optimized (LF) package (Month 12).

Here we exploited 2 grating designs for 1060 nm wavelength: 1st order DFB defined using e-beam lithography and 2nd order DFB defined using holographic lithography. The wafers with gratings were processed and laser diodes for both designs were tested. We found that the first order DFB lasers and second order DFB lasers have shown very similar electro-optical performances.
In order to complete the task, several DFB lasers were packaged in low-frequency (LF) butterfly modules with single mode (SM) polarization maintaining (PM) fiber pigtail. SM PM fiber is required for easy implementation of DFB seed modules into the MOPA fiber laser systems. The laser emission was coupled into the single mode polarization maintaining fiber using anamorphic fiber lens. Power of >200 mW out of the fiber is achieved. Fiber coupling efficiency is ~75%. The spectral characterizations of laser radiation out of the fiber have shown that the lasers are locked to the DFB wavelength for all investigated conditions and the side mode suppression ratio (SMSR) is > 50 dB at I >250 mA, confirming the single longitudinal mode operation.

Task WP2.3: High frequency (HF) packaging for ns pulsing of DFB laser diodes and delivery of pump module with dichroic pump protection (Months: 1-18). (100%)

D2.2: Report on module package assembly optimized for HF operation and delivery of pump modules with dichroic pump protection (Month 18).

For this task we have compiled an equivalent electrical circuit for small signal modulated forward biased laser operating above the threshold in "butterfly" package. Our model predicts possibility to modulate up to 500 MHz for our standard packaging scheme. We identified the ways to improve the modulation speed up to 1 GHz and higher.

The second part of the project was devoted to introduction of the fiber laser pump protection against fiber laser 1060 nm radiation coupled back into the modules. The pump laser radiation with the wavelength in the range between 915-980 nm is coupled into the multimode fiber using fast axis collimating (FAC) and slow axis collimating (SAC) lenses. The high reflectivity coating for the wavelength >1010 nm was deposited on one side of the SAC lens, closest to the fiber entrance. Such coating prevents the backreflected fiber laser emission coming out of the fiber from focusing back into the laser waveguide and consequently from destroying the pump laser.
Using this design we built modules with protection from the fiber laser radiation. We experimentally determined the suppression of 1060 nm radiation by ~40 dB.

Task WP2.4: Complete pulsed operation characterization, final reporting, and delivery of prototypes in high frequency capable packages (Months: 19-24) (100%)

D2.3: Final performance report and prototype delivery (Month 24)

During the final 6 month we focused on improving the capability of developed DFB laser devices for high frequency modulation. The devices were thoroughly characterized using both small signal modulation experimental set-up build at Oclaro and high current subnanosecond pulse modulation using the set-up at MULTITEL.
By changing the chip design and thus reducing the parasitic resistance we were able to extend the small signal modulation (SSM) bandwidth from ~1 GHz up to 4 GHz.
As the next step the DFB lasers were assembled in the butterfly module package with single mode polarization maintaining fiber pigtail and were tested using the subnanosecond current pulses at MULTITEL.
Current pulses adjustable between ~400 ps and 4 nanoseconds were applied to the laser module. The DFB laser in the module optimized for HF operation was capable of producing optical pulses shorter than 1 ns with the wavelength locked at ~1062 nm.

Significant results

1. Manufacturing process of DFB lasers is established at Oclaro
2. High performance 1060 nm DFB lasers are developed
3. High speed modulation of the module packaging is demonstrated
4. Carried out optimization of DFB laser design for ultrashort pulse modulation and successfully demonstrated wavelength stabilization for the DFB laser packaged in the butterfly module driven with subnanosecond pulses
5. ~40 dB suppression of the 1060 nm radiation using dichroic filter is demonstrated experimentally
6. Single emitter pump modules are assembled with such filters for protection against the fiber laser radiation

Explain the reasons for deviations from Annex I and their impact on other tasks as well as on available resources and planning
No deviations from Annex 1.

Explain the reasons for failing to achieve critical objectives and/or not being on schedule and explain the impact on other tasks as well as on available resources and planning
Development of laser pump modules with the dichroic filters was delayed (~4 month) because of difficulties in designing stop band of the filter on the curved surface without affecting the lens optical throughput efficiency at the laser wavelength. Several design iterations were necessary to achieve the required result. Meantime we provided standard laser pump modules without protection to our partners and the pump protection was achieved using the external filter. Therefore it was no impact on the other tasks of project.

A statement on the use of resources, in particular highlighting and explaining deviations between actual and planned person-months per work package and per beneficiary in Annex 1 (Description of Work)
Resources were spent according to the project plan. However the actual spending was lower than planned. Therefore part of the funding for WP2 project was transferred to other work packages.

3. WP3: PCF design, production and testing
Objectives
The aim of Work Package 3 is to develop active, large mode area (LMA) fibers and interfacing technologies for Q-switched and MOPA laser configurations. The work package is closely linked to WP2 for seed- and pump sources and to WP1 for complete laser integration and system tests.
The goal is to leverage the stand-alone photonic crystal fiber (PCF) technology to monolithic solutions enabling high-power pulsed fiber lasers to enter the solar cell market. Objectives for the work package are:

- Optimizing flexible LMA fibers for highest possible power performance.
- Develop interfacing technologies that allow simple access to PCFs.
- Produce non-flexible (rod-type) fibers enabling new laser tools for solar cell materials processing.

The partners involved in WP3 are: NKTP (WP-Leader), UNIPR, EOL, Oclar, UNILJ and MUL.

Summary of progress towards objectives and details for each task
The development in WP3 combines numerical simulations from the University of Parma, fiber drawing at NKT Photonics A/S (NKTP), and fiber laser expertise from Eolite and Multitel.

Task WP3.1: Flexible active LMA fiber with conventional fiber pigtail (Month 1-12, 100 %)

The tasks in WP3.1 have been concluded and the results are described in deliverable report D3.1, which was delivered in time. The work was headed by NKTP with inputs from UNIPR and EOL.

Task WP3.2: Development of modeling tools (Month 1-20, 100 %)
The tasks in WP3.2 have been concluded and the results are described in deliverable report D3.2, which was delivered in time. The work was headed by UNIPR with inputs from NKTP and EOL.

Task WP3.3: Monolithic pump-signal combined, flexible active LMA fiber (Month 20-26) (100%)
The tasks in WP3.3 have been concluded and the results are described in deliverable report D3.3, which was delivered with a delay of five months. The delay on the combiner was not critical for the ALPINE progress, as the fiber laser prototype for solar cell scribing in WP1 was made without it.

Task WP3.4: Rod-type active LMA fiber (Month 22-30,100 %)
The tasks in WP3.4 have been concluded and the results are described in deliverable report D3.4 which was delivered in time. The development is based on a patent pending ROD design developed in the FP7 project LIFT, whence an agreement was made to transfer the foreground knowledge. The results showed that thermal effects have a significant impact on ROD performance. During the M30 progress meeting, it was thus decided to try and reallocate funds for an additional activity on an ROD type fiber incorporating thermal effects. This activity is described below.

Task WP3.5: Rod type active fiber incorporating thermal effects (Month 30-34,100 %)
This task has been added to the originally planned WP3 activity by the GA amendment. The tasks in WP3.5 have been concluded and the results are described in deliverable report D3.5, which was delivered in time. The new ROD has significantly better performance than PCF#3 and NKTP expects to launch it as a commercial product later in 2012.

Significant results
The development up to the fabrication of PCF#1 (D3.1) have resulted in an improved production method, which has been implemented in NKTPs top selling large mode area commercial fiber product DC-200-40-PZ-Yb. This has matured the fiber and it is expected to be transferred from R&D to production in 2012.
A major obstacle for wide spread commercialization is that the fiber is difficult to use. Accordingly the pump/signal combiner to be developed in task 3.2 should increase the addressable market of the fiber significantly.
NKTP started developing a backward pumped combiner in 2010, and made a prototype with excellent performance. However, it was not possible to reproduce this combiner (see D3.3 for details). Independent development in WP1 by Multitel and Eolite showed that the flexible fiber platform was not able to handle sufficient power for making the ALPINE laser demonstrators. Thus, NKTP did not send the single good multiplexer to EOL, but instead sought for a reproducible combiner solution. This involved changing from a backward - to a

forward pumped combiner and outsourcing part of the development to a third source. The details of the combiner are reported in D3.3 which was delivered in Feb-2012. Since then, NKTP has shown that the combiner works very well in a ps amplifier (80 MHz, 5 ps at 1064 nm), where amplification up to 80W output power has been demonstrated.
The combiner was sent to EOL on 29 June 2012, where it will be tested in a ns amplifier in the last months of the project. Subsequently NKTP will sample key customers with starting from Q3 2012 and it is expected that it will be made generally commercially available in 2013.
The results from PCF#2 (D3.2) have so far not resulted in a commercial product. It has been shown that the fibers can successfully suppress non-linear effects, such as ASE. Thus they potentially have better performance than conventional fibers for operation at 1064 nm or higher wavelengths, and for pulsed systems with low repetition rate. So far it is unclear whether the improved performance is sufficient to justify the additional fabrication complexity. Accordingly, NKTP have per 1/1 2012 started a PhD project with the aim of maturing the fibers. It is still to goal to release these fibers as a commercial product in 2013.
The ROD fiber developed for PCF#3 (D3.4) showed large promise, but was difficult to reproduce and had issues with thermal effects. It was proposed as a corrective action to reallocate funds to NKTP and UNIPR to develop a fourth fiber in a new task 3.5.
The resulting ROD fiber has been fabricated in early June-2102 and did indeed have the desired properties:

- Wide single mode guidance region from 1030 nm to 1110 nm.
- High power operation with a single mode output; 175 W output shown
- Excellent output power stability: over 200h test with 50 W output.

Thus NKT Photonics is planning to launch it as a commercial product later in 2012 (for further details see report D3.5).
WP3 had furthermore led to two master projects at the University of Parma, one master project at The Technical University of Denmark (DTU) with NKT as co-supervisors. Furthermore DTU and NKTP have in January 2012 started a PhD project to further develop the fiber concept, which was used for D3.2. The work in WP3 has been disseminated in 5 journal publications and 13 talks at peer reviewed conferences. The dissemination has mainly been driven by UNIPR.

Explain the reasons for deviations from Annex I and their impact on other tasks as well as on available resources and planning
The deliverable D3.3 on the pump/signal combiner for the flexible fiber was delayed five months. However, this delay was not critical for WP1, as their experiments showed that a ROD fiber was necessary for the ALPINE lasers.

A statement on the use of resources, in particular highlighting and explaining deviations between actual and planned person-months per work package and per beneficiary in Annex 1 (Description of Work)
The partners have used their entire budget including the requested reallocation.

Furthermore, NKTP has outside ALPINE financed development of the pump/signal combiner at a cost of approximately 50k.

4. WP4: Thin film solar cell production

Objectives

The aim of this WP is to prepare and supply to all the other partners samples of solar cells of both CdTe/CdS and CuInGaSe2/CdS deposited on different substrates such as glass, polyimide and metallic foils. Results on the module characterization and validation here performed are also part of WP7 activity and will not be reported once again in WP7 section. The partners involved in WP4 are: SSE (WP-Leader), NEXCIS, ZSW, WS, UNIVR.

Summary of progress towards objectives and details for each task

Within the WP, there are two main groups: one made up of industrial partners and the other are of research laboratories. The first part consists of SSE, NEXCIS and WS which respectively produce: CdTe PV modules based on rigid substrates, CIGS PV modules on rigid and flexible substrates, CIGS modules on glass substrates. The second part consists of SSE, ZSW and University of Verona which respectively produce: CdTe, CIGS and CIS solar cells both on rigid (glass and ceramic) and flexible substrates, CIGS solar cells and modules both on rigid and flexible substrates and CdTe both on rigid and flexible substrate.

SSE

SSE has continued his research with respect to the CdTe-based cells in substrate configuration and on CIGS-based cells both on glass and on ceramic substrates.

1. CdTe modules at different stages of fabrication for P1, P2 and P3 laser scribing. 10x10 cm2 and 30x30 cm2 mini-modules were sent to Multitel.
2. CIGS based solar cells completely fabricated by sputtering and selenization. SSE innovation consists in the use of the sputtering technique to deposit the starting precursors (In2Se3 or InSe e Ga2Se3 or GaSe) and a consequent selenization in pure Se atmosphere. Results on SLG (Soda-Lime Glass) are summarized in the next table:

With the innovative method of deposition of the composite precursors developed by SSE and described before an important result was obtained by using as a substrate ceramic commercial tiles. A photovoltaic conversion efficiency of 13.95% was reached and this is one of the highest value ever obtained on ceramic substrates.

In this period SSE produced a lot of CdTe and CIGS samples used for the laser scribing test. In fact, by September 2011, SSE installed a machine for laser scribing in the Thin Film Laboratory (ThiFiLab) of the University of Parma.

In a first stage, the scribing machine was equipped with a conventional solid-state laser, which works both at 1064 and 532 nm. Later on the scribing system was equipped first with a fiber laser built up by the laboratory of Stefano Selleri at the Universty of Parma and secondly by a fiber laser produced by EOLITE.

The first fiber laser installed worked only at 1064 nm. Some results so far obtained on TCO samples normally used in CdTe/CdS solar cell fabrication are shown in the following. Results

of comparison of a P1-scribing performed by a commercial solid-state laser and a P1-scribing carried out with the UNIPR laser show the great finesse difference of the fiber laser. The typical laser parameters are: Ap (Average power) =1W, Pw (Pulse width) = 20ns, RR (repetition rate) =100KHz, SS (Scribing speed) = 1m/s. Also P2 and P3 scribings tests, carried out on CdTe/CdS modules by using Eolite fiber-laser, shown very clean and sharp edges and they arent affected by the thermal damage (HAZ) usually observed in CdTe standard manufacturing.
CdTe mini-modules, with an area of 10x10 cm2, by testing a fiber laser scribing at a time were made. This allowed us to characterize in detail the single scribing carried out with new fiber lasers by finishing the module with traditional scribing.
With Eolites fiber laser many tests on CIGS-based mini-modules (dimension of 10x10 cm2) sent from ZSW have been performed. It has been thought to proceed as for CdTe-based minimodules. Experiments are underway and we have been successfully performed the P1 scribing (at 1064 nm) and P2 (at 532 nm). Some 10x10 cm2 CIGS-based minimodules equipped with P1 scribing directly made by ZSW were tested in our laboratory for P2 scribing and then re-sent to ZSW that will carry them out by running the P3 scribing in traditional way (mechanical scribing). In this way it will be clear the behavior of the P2 scribing realized with the Eolite fiber-laser at 532 nm on CIGS-based mini-modules in respect to standard P1 and P3 traditional scribing. The electrical characterization of the different processing steps certifies in all cases an efficiency around 10%.

NEXCIS

NEXCIS started to provide electrodeposited based CIS on glass at month 2 (2 months before the compromise acquired in the project) and CIGSe at month 12. During the last months NEXCIS has validated and increased the quality of the absorbers and devices that were scaled up to 60x120 cm2 size. Wafers of this size (and size smaller than this) have already been sent to laser partners, especially for testing of the automated machine. Moreover, complete modules have been sent to JRC for measurement of standard modules to be used as reference at NEXCIS. More samples have been sent to LPKF for final scribing and final modularization at NEXCIS.
Here the results acquired in the project activity are reported. The best efficiency is 13.9% (by Newport in the US) for a cell (~0.5 cm2), medium efficiency is 12.2 for 95% of the wafer surface (for a 30x60 cm2 wafer), and 11.6% for 100%. An efficiency of 8.2% for a 30x60 cm2 module was communicated. Today, efficiency for a pixel is certified at 14.0% (by Newport in the US) for a cell (~0.5 cm2), in case of internal measurements we have measured a cell at 14.9% (under certification measurements), medium efficiency in a wafer is 13.2 for 95% of the surface of the wafer, and 13.7% for 100%. There has being also a big reduction in the gap between wafer and modules, and 30x60 cm2 modules are now obtained in a repeatable way with efficiencies at about 10.7%. The record efficiency for encapsulated modules is 12.3% as certified by Certisolis.
However what it is more important, 60x120 cm2 wafers with a medium efficiency of 11.2% (12% for 90% of the wafers) are obtained in our baseline, which will be providing in near future with modules 60x120cm2 with efficiencies larger than 10.5%.
The process portability on flexible metallic substrate has been fully demonstrated. However, due to more work needed with the right encapsulation material, metal and polymer

modules are in stand-by due to reliability issues not concerned with NEXCIS process but, more in general, to lightweight thin film objects. In this sense NEXCIS has focus all activities in glass-glass solutions.
Pre-qualification of the 60x120 cm2 reactor for electro-deposition of Cu, In and Ga is already achieved. The same pre-qualification has been achieved for the furnace developed by NEXCIS. NEXCIS is at present working in validating the yield, throughput and economic issues to go towards industrial pilot line conditions, which is foreseen at the end of 2013.
At present, more than 90 employees are working at NEXCIS facilities while at the beginning of the project less than 10 employees were working at NEXCIS.

WS
Wurth Solar was able to deliver CIGS modules on large glass substrates after any relevant processing appropriate for laser scribing tests (P1-P3, edge cleaning). Wurth Solar organized to be able to respond flexibly and quickly to partners with substrates as soon as required. WS has sent standard modules (P2, P3 mechanically patterned) to JRC for validation to obtain a reference for the laser scribed samples.
During the last months of the last year, WS was partially acquired by MANZ GmbH. Only in late April 2012 it was clear that this partner was yet inside the Consortium. For this reason WS has considerably reduced its activity during the last months of the project. WS sent mini-modules to UniPr for scribing test in M36.

ZSW
ZSW has continued to deliver CIGS modules with sizes of 10 cm x 10 cm as samples for the testing of patterning lasers to the partners LPKF, MULTITEL and University of Parma. These samples included modules ready for the application of all three patterning steps. Also, additional samples carrying an array of 81 test cells for the purpose of P3 quick tests in the laser labs have been delivered.
For the purpose of having reference samples with known electrical properties, one out of each set of nine samples was completed using conventional patterning at ZSW. These references reached efficiencies of up to 15%. This improvement of about 1% compared to previously reported reference samples is due to improved deposition parameters for the sputtering of the zinc-oxide front contact which lead to an increase of the open circuit voltage of the devices.
Furthermore, additional modules on flexible substrates - polyimide film with a thickness of 25 µm - have been fabricated and sent to MULTITEL for testing patterning steps P1, P2, and P3.
Flexible substrates made from steel foil covered by a barrier layer have been prepared. This silicon oxide barrier layer, which is about 1 micron thick provides the electrical insulation of the subsequently deposited Mo back contact layer and of the individual cells. Sample have been sent to MULTITEL for P1 scribing experiments.
Samples returned from the partners LPKF and MULTITEL after scribing tests have been completed and analysed in the ZSW laboratory. Results are quite promising:

- P1 laser-scribed at MULTITEL (sample 294002) leads to module performance comparable to standard P1 patterning at ZSW.

- P2 laser-scribed at MULTITEL (samples ??WS?? and 138667) showed a somewhat increased series resistance, which deteriorated the module performance by about 1% absolutely. While optical and electron microscopy show a smooth Mo surface within the P2 scribes, EDX (energy dispersive X-ray spectroscopy) reveals some remnants of CIGS on the surface, which probably are responsible for the increased contact resistance observed.
- P3 laser-scribed at MULTITEL (sample 2003475) was comparable with conventional mechanical scribing. After measuring the I-V curves of the module, an additional P3 scribe was applied. Thereby, mechanically scribed lines were placed aside the laser lines in a way that the lines mechanically scribed replace the laser lines, reducing the cell active area by a small amount. The changes in the I-V curves indicate that there is only very little shunting due to laser P3.
- P2 laser-scribed at LPKF (sample 295865): The Mo layer was completely removed in the centre of the P2 lines. Only at the borders of the lines a few micrometers of the back contact were preserved. Nevertheless, this small Mo stripe could be used as contact. Of course, the contact resistance was increased, but the module performance was reduced by about 1% absolutely only.

P3 laser-scribed at LPKF (sample 295988): The I-V curve of the module indicates significant shunting in accordance with the results of the analysis of the test cells. From microscopical inspection it seems clear that the quality of the P3 scribes can be improved by reducing pulse energy and overlap. But even with the parameters used the module performance is reduced by less than 1% absolutely.

UNIVR

In UNIVR labs, solar cells have been fabricated by depositing each single layer (except for the front contact), namely CdS, CdTe and back contact, by vacuum evaporation.
For the preparation of the samples to be scribed by the laser partners we have prepared and optimized a complete fabrication process for deposition on glass and on polymers, so by applying a lower temperature process compared to the typical ones that use substrate temperatures above 500°C.

Front-contact deposition

For transparent conductive oxides (TCO), that make the front contact of the device, two different glass coatings have been used: a commercially available ITO film coated glass with a SiO2 barrier layer and a laboratory scale bi-layer of conductive ITO + thin insulating ZnO, deposited at high temperature. The first one is a commercially prepared ITO with a thickness of 180nm and a sheet resistance of 10 Ohm/square. The second one is a 400nm ITO+100nm intrinsic ZnO deposited by radio frequency-sputtering at a temperature of 400°C with a sheet resistance below 5 Ohm/square. Due to its high substrate deposition temperature this layer is much more crystallized and stable; moreover because of the ZnO layer, which acts as a barrier to diffusion of impurities, indium diffusion is avoided. A comparison of the devices made on these two different substrates will outline some of the properties observed.

Window layer fabrication

CdS is evaporated in vacuum at a pressure of 10-6 mbar using direct current heating of a molybdenum crucible and deposited on the glass/TCO stacks at a substrate temperature of 150°C with a deposition rate ranging from 0.15nm/sec to 0.45nm/sec (controlled by a quartz crystal thickness monitor). After deposition, CdS was annealed by heating the stacks in vacuum for 30 minutes (in order to increase the stability of CdS to the subsequent depositions and CdTe activation treatment), a slight re-crystallization of the grains was observed by AFM with an enlargement of the grain size from 50-100nm to 100-200nm, not shown here.

CdTe deposition and post-deposition treatment

After deposition and treatment of the CdS layer, CdTe is deposited in the same chamber by heating a special in-house made graphite crucible at a substrate temperature ranging from 300°C up to 340°C and deposition rate of about 2 nm/sec. A typical CdTe layer for these devices is 3.5/4 micron thick with quite compact morphology and grain size of about 1 micron as shown in Fig. 7; we have observed that the morphology and the grain size is depending not only on the substrate temperature but also on the TCO. CdTe deposited on commercial ITO and ITO+ZnO shows a similar but not same morphology, grain size is typically around 1 micron for both but it results to be much more compact in the second case. Compared to the close space sublimated (CSS) deposited CdTe grains (which have a much higher substrate temperature) are quite small and activation treatment is needed also for increasing the grain size.

It is known that for a good cell performance an activation treatment is necessary. Generally, in order to enhance the grain size and passivate the grain boundaries in the CdTe polycrystalline structure a layer of CdCl2 is deposited on top of the CdTe and then annealed in air. We have prepared two different activation processes: the standard CdCl2 treatment and the alternative treatment with chlorine containing gases (Freon).

The CdCl2 treatment is, in our case, applied by preparing a saturated solution of CdCl2 in methanol. Optimization of the device has brought to an optimum temperature of 410°C. The number of drops of saturated solution is also an important factor in order to define the optimized quantity of CdCl2 to have the right compromise between CdTe activation and excess in CdS/CdTe intermixing.

For Freon treatment, an as-deposited cell is treated in a vacuum chamber at high temperature in a controlled mixture of chlorine containing gases (difluorochloromethane, HCFCl2, Freon R-22) and Argon (with pressures from 10 up to 60 mbar for Freon and of 500 mbar for Argon).

A lot of experiments have been done to optimize this activation treatment on the low temperature deposited CdTe layers. This process was introduced for the first time in order to get rid of the more dangerous CdCl2. Different device have been produced with an activation time between 5 and 25 minutes at temperatures between 400°C and 450°C. At around 400°C Freon dissociates, freeing chlorine, which, reacting with CdTe, forms CdCl2 which re-crystallizes the CdTe layer and passivates the grain boundaries.

The recrystallization mechanism has been studied by means of atomic force microscopy (AFM) and X-ray diffraction spectra, not shown here.

Back contact

Back contact was made by vacuum evaporation of Cu/Au stacks. Subsequently an annealing of the back contact is applied at 200°C in air for 20 minutes in order to diffuse Cu in CdTe and make an ohmic contact.In case of CdCl2 treatment, a Bromine-Methanol etching is applied in order to remove the CdCl2 layer and to prepare the surface for the Cu/Au deposition, however the removal of the CdCl2 in case of wet treatment was quite difficult. In case of Freon treatment, the treated CdTe film is not etched since the surface is free of CdCl2 (re-evaporated at high temperature in vacuum) and a tellurium rich layer is made during the activation process.
Deposition of copper results to be very sensitive, a higher amount of copper improves the back contact also doping the bulk CdTe but reduces the shunt resistance (Rsh) resulting in a lower fill factor. The amount of copper has been tuned for the differently treated CdTe layers. A more conductive absorber would need less copper to improve the performance.

Several photovoltaic devices have been made with different parameters of both CdCl2 and Freon treatment for CdTe deposited on the different stacks described before.
The highest performance was given by CdCl2 treated cells and with stronger CdS/TCO stacks, this means that the most performing TCO was the one made with high temperature deposited ZnO/ITO with enhanced ability and prevention of sodium and indium diffusion. Moreover only 2 nanometers of copper with 50 nanometers of gold are necessary for a good contact. With this configuration efficiencies exceeding 13.5% are routinely obtained. If Freon treatment is applied, much lower efficiencies are measured: highest efficiencies are obtained with 8 nm of copper, however a much lower shunt resistance (Rsh) gives lower fill factors and lower open circuit voltages.
If a 2 nm copper contact is applied on these Freon treated cells a very low efficiency is performed. Anyway with more aggressive Freon treatment (by higher Freon partial pressures or higher temperature) bigger grain size is obtained but not higher efficiencies. Excess of Freon pressure have resulted in shunted device. So the required copper amount is also depending on the different CdTe treated layer. We have registered that in case of Freon treated CdTe devices four times the amount of copper is needed for a reasonable efficiency compared to the CdCl2 treated cells. This is consistent with the fact that activation by Freon is much weaker than the one made with CdCl2 as reported above. On the other hand, using a lower amount of copper allows to have a better working cell and this results in a higher efficiency.
Cells made with CdCl2 treatment exhibit efficiencies from 10 to 13.5%, with current in the range of 22 to 25 mA/cm2, Voc exceeding 830mV and FF from 60 to 70%. The relatively low Voc and FF are connected with relatively low Rsh. This can be explained by an excessive consumption of CdS into the CdTe layer. The best results were obtained with thicker CdS (more than 500nm) annealed in vacuum at 450°C. Freon-treated cells show lower efficiencies than CdCl2 treated ones. The highest achieved efficiency for this treatment is 8.7%. Although the Freon treated cells would not need a post deposition etching, a good ohmic back contact was not easily reproducible. Many of our Freon-treated cells have shown a kink on the positive part of the curve.

Transport properties.

For device characterization two different types of cells made with vacuum evaporation were taken into consideration: one activated by Freon and one activated by CdCl2. Moreover cells made by close space sublimation at the University of Parma, were successfully activated by HCF2Cl gas, with efficiencies exceeding 10% as a reference with the low temperature deposited cells.

A standard technique which is very often applied for determination of the doping level in semiconductor junctions is capacitance voltage (C/V) profiling. However, in the presence of deep levels free carrier concentrations determined by C/V profiles can be subjected to large errors. This can be overcome by drive level capacitance profiling (DLCP), as DLCP is a fully dynamical measurement giving undistorted doping distributions. For junctions without deep traps, adjusting their charge state to the DC bias, DLCP and C/V profiles coincide, so the difference between the C/V and DLCP profile gives a lower bound for deep defect concentration active in a given measurement conditions (i.e. temperature and frequency). The capacitance measurements were performed with an Agilent E4980A LCR meter controlled by LabView via computer. Doping concentrations in the space charge region (SCR) of CSS-Freon, VE-CdCl2 and VE-Freon samples were estimated to be 2x1014 cm-3, 6x1013 cm-3, 3x1013 cm-3, respectively. Deep defects contributing to capacitance-voltage profiles were also detected. The difference between the C/V and DLCP profile, indicating the lower bound for the concentration of deep defects following the DC bias sweep, is also the highest for the CSS-Freon sample and amounts 4x1014 cm-3. For the VE-Freon device the defect concentration varies from 1x1013 cm-3 at 2 µm up to 2.3x1014 cm-3 at distances larger than 2.5 µm. In the VE-CdCl2 sample we detected no large differences between the C/V and DLCP profiles around RT.

Flexible cells

The same optimized process has been applied to the flexible polymer substrates. Prior to this, a study of the different polymers have been made. Different polymers (some of them are not on the market but still in prototype form) were taken into consideration: DuPont (Kapton), Kaneka, UBE (Upilex) and Mitsubishi (Neopulim). For Kaneka and DuPont a smaller thickness must be used. Indeed, the 25 micron thick substrates are almost brown, cutting transparency below 400 nm for Kaneka and Kapton. Mitsubishi polymers, however, have a higher transmittance at low wavelengths even if they remain opaque (probably still need to reduce the thickness).

The polyamides have been tested with an annealing in order to check their temperature resistance to the deposition process, treatments were made for 30 minutes at 370 °C and at 450 °C degrees in air. Flexible solar cells have been fabricated by using Upilex foils12.5 microns thick. For the CdTe deposition process and post-deposition treatment, the same process optimized on glass was used also for the polymer substrate.

Morphological and crystallization parameters have been studied with atomic force microscopy and X-ray spectroscopy. CdTe on flexible substrates grows similarly as on glass, in terms of grain orientation and size. However some restrictions come from the limited transparency of the polymer substrate. Polymer looks yellow in color.

Significant results

- The objectives for the CdTe-based cells made on substrate configuration have been achieved.
- CdTe and CIGS mini-modules have been made in traditional way for reference.
- CdTe and CIGS mini-modules in various stages of realization have been made and sent to all the scribing partners who have requested them.
- High efficiency CIGS-based cells made on ceramic substrate have been realized. Some of them have been used for testing the laser scribing.
- The SSE scribing work is intensively continuing both on CdTe and CIGS samples. P1, P2 and P3 on CdTe minimodules were definitively developed and optimized. Fiber-laser scribed CdTe minimodules were made and sent to JRC for characterization. Results are very encouraging in order to use this technology for solar cell processing.
- Low temperature vacuum evaporated high efficiency CdTe solar cells both on rigid and polymeric flexible substrate were realized and cells in different stage of fabrication were sent to all the scribing partners who have requested them.
- Successful scale-up from 15x15 cm2 to 30x60 cm2 on glass substrate and preliminary to 60x120 cm2 at NEXCIS.
- Today NEXCIS efficiency for a pixel is certified at 13.9% (by Newport in the US), medium efficiency in a wafer is 12.2 for 95% of the surface of the wafer, and 11.6% for 100%.
- The process portability on metallic substrate has been fully demonstrated.
- Prequalification of the 60x120 cm2 reactor for electrodeposition of Cu, In, Ga is already achieved.

Explain the reasons for deviations from Annex I and their impact on other tasks as well as on available resources and planning
Considering the great amount of exchange of modules by partners, the consortium agreed to demonstrate the feasibility of the laser patterning process by producing a series of 30 cm x 30 cm mini-modules for CIGS and 10 cm x 10 cm mini-modules for CdTe. In this way all the scribing systems can participate to the effort to build PV modules fully scribed with fiber laser. Moreover these dimensions are sufficient to demonstrate the scalability at an industrial level of the scribing made with fiber-laser.

Explain the reasons for failing to achieve critical objectives and/or not being on schedule and explain the impact on other tasks as well as on available resources and planning
So far no critical objectives have been failed.

A statement on the use of resources, in particular highlighting and explaining deviations between actual and planned person-months per work package and per beneficiary in Annex 1 (Description of Work)
The use of the allocated resources has been as planned, but WS whose reduced participation during the last months resulted in a reduced actual budget.

5. WP5: Laser scribing and beam handling

Objectives

The aim of Work Package 5 is to integrate the laser source developed in WP1 in a machine concept. That includes the beam handling and new concepts for the beam splitting. On that machine industrial like laser scribing of solar panels shall be achieved.

The partners involved in WP5 are: LPKF (WP-Leader), EOLITE, NEXCIS, ZSW, WS, UNIVR, ES.

Summary of progress towards objectives and details for each task

Task WP 5.1 First scribing machine prototype (100%)

The scribing machine was designed and built upon requirement specifications taking into account the different technologies to be tested (CdTe and CIGS) as well as production related issues like accuracy and throughput. As a result the machine is capable of processing substrate and superstrate configurations at high speed being flexible in providing a platform for different laser sources and optical configurations.

Task WP5.2: Test of the MOPA laser prototype (100%)

The final MOPA test laser has been integrated into the Alpine test system in Garbsen and tested with both wavelengths 532 nm and 1064 nm at a pulse length of approx. 500 ps on all test materials provided by the partners SSE, University of Verona, Nexcis and ZSW. Tests with the state of the art picosecond laser source and the beam shaping plate have made at Multitel and using the Q-switch laser from WP1.4 SSE performed further scribing test. Samples were sent back and forth for testing and further processing and final mini-module performance compared to those manufactured with standard scribing methods.

Task WP 5.3 Beam shaping test and Q-switched laser integration (100%)

The first approach by LPKF has been to use a special beam shaping optic providing a quasi-top-hat profile in order to reach a higher depth of focus compared to the one achievable with exact top-hat intensity profiles. The result gives a good top-hat approximation with a depth of focus around +/- 400 mm at 532 nm. This result has been compared to a fiber-based top-hat generation done by EOLITE.

Task WP5.4: Final optimization of the scribing machine (100%)

Components of the Alpine test system have been optimized in their design aiming at highest throughput and accuracy. The main components influencing the tact time of scribing are the scribing and glass transporting axes. LPKF has worked on two different axis designs which are currently set-up on a test bench and are going to be evaluated regarding acceleration, speed, accuracy, heating taking into account large and heavy loads as 4 mm thick substrates of up to GEN5 sizes as well as free flying optics. ZSW has tested and compared scribed test modules from all participating partners to conventional scribed ones. Laser scribing has already proven to be a promising alternative to mechanical scribed CIGS modules.

Significant results

- Laser scribing machine capable of running of up to 2 m/s on the scribing axis.

- Laser scribing machine designed to perform film-side and glass-side scribing comprising a flexible exhaust system to process CdTe modules as well as CIGS modules.
- Design and test of a beam shaping module providing good top-hat approximation with an excellent depth of focus.
- MOPA Laser has been integrated in Alpine test system and extensive scribing tests and parameter improvements on all relevant material systems have been carried out.
- CIGS Samples with P2 scribed at LPKF using enhanced parameters have been completed and analysed at ZSW. The I-V curves indicate a good P2 scribe quality.
- P3 laser-scribed CIGS sample at MULTITEL was comparable with conventional mechanical scribing.

Explain the reasons for deviations from Annex I and their impact on other tasks as well as on available resources and planning
No deviation from Annex 1, but additional support to LPKF for the laser scribing activity by Multitel, SSE and UNIPR.

Explain the reasons for failing to achieve critical objectives and/or not being on schedule and explain the impact on other tasks as well as on available resources and planning
No objectives have been failed.

A statement on the use of resources, in particular highlighting and explaining deviations between actual and planned person-months per work package and per beneficiary in Annex 1 (Description of Work)
The use of the allocated resources is as planned according to the GA amendment n.3 aimed to support LPKF laser scribing activity with the additional work of Multitel, SSE and UNIPR.

6. WP6: Automation

Objectives
The goal of this WP is to study, develop and test standard parameters in order to produce system integration guidelines and to realize systems to focus and guide the laser beam.
The partners involved in WP6 are ES (WP-Leader), QUANTA and LPKF.

Summary of progress towards objectives and details for each task

WP6.1 Standards for automation integration in scribing systems (100%)
The first task is addressed into developing rules for integration and experiences in the real industrial environment. The activity were dedicated to collect information and experiences with partners and to attend important European fairs to understand needs of the market and to identify issues to be faced. In this package were assessed important parameters for the laser integration like temperature effects (gradients and stability), laser scribing panel feeding, mechanical stress, systems integration issues. The integration of the protocol

developed by Quanta to manage the device they developed in an industrial network has been studied and implemented.

Wp6.2 Laser beam moving and focusing system (100%)
The WP has developed a suitable focusing head achieving a stable and reliable processing of the glass. Due to changes in the focal position the spot diameter changes accordingly and so the power density on the layer to be processed. Allowing a dynamic focusing of the laser beam brings to a higher stability of this parameter and consequently of the ablation rate. The core philosophy of the compensation system is a matrix camera and a focus system develop with the collaboration of all the WP partners.
The WP also developed a reliable moving system with adequate precision in order to explore and test the feasibility of a guiding system as well as a cost effective and less precise moving system with acceptable results. The moving system moves the sample under test below a fixed laser and guiding system which is composed by two linear axis in a table configuration. Details of focusing and moving systems are reported in deliverables D6.2 and D6.3.

Significant results
A practical, computer controlled high-end dynamic guiding system has been developed that allows for tracking of the glass scribed waviness on thin films solar cells.
A microprocessor controlled high-end dynamic focusing system has been developed that allows for fast tracking of the glass deformations on thin films solar cells.

Explain the reasons for deviations from Annex I and their impact on other tasks as well as on available resources and planning
No deviation is registered, but moving D6.2 to M33 as agreed with PO and PTA.

Explain the reasons for failing to achieve critical objectives and/or not being on schedule and explain the impact on other tasks as well as on available resources and planning
No critical objectives have been failed.

A statement on the use of resources, in particular highlighting and explaining deviations between actual and planned person-months per work package and per beneficiary in Annex 1 (Description of Work)
The use of resources has been in line with the planning. No deviation were claimed.

7. WP7: Testing of PV devices and scribing process validation

Objectives
The objective of WP7 is to evaluate the quality of photovoltaic thin film modules patterning on devices realized in different configurations (substrate/superstrate) and on different substrate materials (glass/flexible). Both CIS and CdTe modules are researched. The idea is to define a set of suitable tests leading to correctly identify potential critical aspects both at cell level and at module level. Similar measurements are also carried out on state-of-the-art

solar modules with conventional processed patterning and edge cleaning, in order to provide a benchmark against which to highlight process improvements by laser use.

The partners involved are JRC (WP leader), ZSW and University of Verona as research centres, together with SEE, Nexcis, Wurth Solar and LPKF as industrial partners. Multitel has also been involved in the scribing work to prepare devices.

The agreed strategy of the consortium is to demonstrate the feasibility of the PCF laser patterning process by producing a series of demonstration devices (30 cm x 30 cm mini-modules for CIGS and 10 cm x 10 cm mini-modules for CdTe). It is noted that this device production and activity is partly in common with WP4.

To enable assessment of each of the scribing steps as well as the overall working device, each combination (that is CdTe or CIGS on glass or flexible substrate, substrate or superstrate configuration, scribing steps) has included, as a minimum, a group of 4 sample devices with different characteristics according to the scribing process P1, P2 or P3. Details can be seen in the deliverables D7.5 and D7.6.

The verification testing uses the methods described in Deliverables D7.3 and D7.4. The electrical performance tests on one of the four samples include as a minimum spectral response and current-voltage (IV) characteristics at standard test conditions (STC). These have been complimented by dark IV, thermography and LBIC depending on time and resources are available.

Summary of progress towards objectives and details for each task

The activities performed are clearly explained in deliverables D7.5 and D7.6 and summarised as follows.

Task WP7.2: Validation of thin film modules realised in a substrate configuration (CIS) on glass and processed by means of advanced fibre lasers (100%)

ZSW has prepared and characterised devices scribed at LPKF. This work is reported in WP4.

Task WP7.3: Validation of thin film modules realised in a substrate configuration (CIS) on flexible substrates and processed by means of advanced fibre lasers

Devices have been prepared using polyamide and steel foil substrates. Scribing trials tried to cope with the waviness and flexibility of the substrate. The process is critical.

Task WP7.4: Validation of thin film modules realised in a superstrate configuration (CdTe) on glass substrates and processed by means of advanced fibre lasers (100%)

SSE has prepared and characterised devices scribed at the SSE/University Parma facilities. JRC has validated the electrical performance of the devices. A series of devices has been prepared by University Verona. Results are reported in the updated version of D7.6.

Task WP7.5: Validation of thin film modules realised in a superstrate configuration (CdTe) on flexible substrates and processed by means of advanced fibre lasers

A series of devices has been prepared by University Verona. The scribing process is still critical.
Results are reported in the updated version of D7.6.

Significant results
Concerning the most suitable analytical methods to evaluate the scribing operations, the following have been identified as the most feasible for a correct check on the quality of laser scribing process:

- Optical microscopy
- Scanning electron microscopy
- Electrical insulation test
- I-V characterization of solar cells
- Thermal imaging
- LBIC mapping.

Measurements according to the first three methodologies have been performed just after laser scribing process, in order to rapidly identify potential faults; I-V characterization and thermal imaging have been then implemented at a later stage, when a completed cell or module is assembled. Tests are also considered in the field of validation of thin film modules comprising IV curve @ STC indoor and outdoor, stabilization cycles, spectral response, TCO and matrix.
In particular, referring to IV curve measurements @ STC conditions, a dedicated research activity is ongoing at JRC, focusing on the measurements methods for improving the compliance among indoor and outdoor measurement results.

As indicated in the above table, an extensive effort is being made to produce demonstration devices using the laser patterning techniques developed in the project.

The performance verification of the following device combinations is already at an advanced stage:
- CdTe on glass substrate with PCF laser scribing (SSE and University Parma)
- CIS on glass substrate with PCF laser scribing (ZSW with LPFK, ZSW with Multitel /University Parma)

In additional the performance verification of CdTe on glass substrate produced by University Verona together with LPKF and Multitel scribing using Alpine lasers is fully completed.
Results are reported in the updated version of D7.6.
Results to date indicate that PCF laser scribed devices are very promising and laser technology is very effective for glass substrate modules. Flexible substrate ones proved to be more critical.

Explain the reasons for deviations from Annex I and their impact on other tasks as well as on available resources and planning
The WP7.2-7.5 activities are largely dependent on the availability of laser-patterned devices from other WPs. The supply of these has been delayed, largely due to problems with availability of lasers for the scribing operations. At the General Assembly Meeting on 28 September 2011 the consortium agreed to enforce the laser scribing activity (GA amendment n.3) to catch up the delay. In addition a detailed planning to complete the work in remaining months of the project was agreed at the Executive Meeting held 28 March 2012, and these actions allowed the first modules to be already fabricated and validated.

Explain the reasons for failing to achieve critical objectives and/or not being on schedule and explain the impact on other tasks as well as on available resources and planning
The overall objective of the work package has been maintained, i.e. to demonstrate the quality of patterning/scribing of CIS and CdTe thin film technologies on glass substrate using advanced pulse conditioned lasers, however successful tests on flexible substrates have not yet been achieved. Partners are still working on it, even after the project end date.

A statement on the use of resources, in particular highlighting and explaining deviations between actual and planned person-months per work package and per beneficiary in Annex 1 (Description of Work)
The use of the allocated resources is below the planned level, consistent with the delays encountered in the supply of devices.

Potential Impact:

The aim of the ALPINE project has been to develop advanced laser processing as a cost effective and high performance technique for the fabrication of novel solar cells, to stimulate the advance of laser industry and to enable growth in the high volume production of solar cells in the near future. In fact, laser processing is expected to be an important and growing production technique for this application. While laser micromachining is widely employed in the laboratory fabrication of some of the worlds highest efficiency silicon solar cells, in most instances the focus of the development is on cell performance with little regard to the manufacturing aspects in high volume. It was one of the objectives of this project to bring high efficiency laboratory cells closer to commercial reality by focusing on the manufacturing aspects with particular regard to high-speed laser processing. The availability of low-cost maintenance, reliable, robust and high efficiency laser sources will be a strong benefit for laser manufactures and integrators as well as for photovoltaic industry.

With the rapid growth of the solar photovoltaic industry in Europe, Japan and the USA, continued support should be given to enable these manufacturers to develop their technology to compete in this growing international market. As a result of the expertise gained through participation in this project, industrial partners will have the possibility to sell innovative and advanced production tools based on the novel technology. Strong-added value will stem just from carrying out the work at a European level. Continuous research and development is the key for superior products with high quality and cutting edge technologies.

These aims and objectives have been successfully achieved by the Alpine consortium which has been able to concretely target specific results with clear market exploitation. The expected exploitable results identified by the project consortium are listed in the following and are explained in details in deliverable D8.4: ��Final version on exploitation prospects, on rising public participation and awareness and plan for using ther disseminating knowledge��.

List of exploitable results.

a. Laser prototype with MOPA laser architecture: MOPA nanosecond laser.
b. Sub nanosecond pulsed source.
c. Q-switched laser.
d. Picosecond laser.
e. Laser prototype with MOPA laser architecture: DFB laser diodes.
f. Laser prototype with MOPA laser architecture: Pump laser with dichroic protection.
g. Active single-mode large mode area photonic crystal fibers (PCFs) for use in high peak power Q-switched and MOPA lasers: Fiber product based on PCF#1.
h. Active single-mode large mode area photonic crystal fibers (PCFs) for use in high peak power Q-switched and MOPA lasers: Fiber product based on PCF#2.
i. Pump signal multiplexer.
j. Single mode fiber ROD for ultra large peak power lasers.
k. Efficient low cost PV devices made by thin film solar cells on flexible and/or polymer substrates Development #1.
l. Efficient low cost PV devices made by thin film solar cells on flexible and/or polymer substrates Development #2.
m. Efficient low cost PV devices made by thin film solar cells on flexible and/or polymer substrates Development #3.
n. 120 x 60 cm2 12% efficiency modules for P1, P2 and P3 scribing and edge cleaning. Development #1.
o. 120 x 60 cm2 12% efficiency modules for P1, P2 and P3 scribing and edge cleaning. Development #2.
p. CIGS with sputtering deposition process on different substrates.
q. New machine axis designed for the top scribing process.
r. New PV laser scribing process to substitute the last two mechanical scribing stages of a standard monolithically integrated solar module.
s. Gaussian to Top-Hat Converter.
t. Laser Beam moving and guiding system.
u. Laser Beam focusing system.
v. Low cost EOM for Q-switching.

Besides laser scribing as applied in the Alpine project, fiber laser have a very huge application potentiality. In Fact fiber laser technology includes high power pulsed and CW fiber lasers at wavelengths ranging from UV to IR. Fiber lasers feature numerous application areas, ranging from both classical and novel industrial applications to environmental monitoring and medicine. Specifically applications in high power fiber lasers will include LIDAR, oil and gas exploration, homeland security and perimeter monitoring.
In addition to enhancing and even replacing existing solutions in a diverse number of demanding industrial and medical applications, novel and important new applications for fiber lasers are emerging as applications specialists investigate the performance features and flexibility of the all-fiber solution.
In the following the main features of fiber laser will be described. Then some of their applications will be presented, in defence and space, material processing, medical industry and medicine as surgical and diagnostic device.

Fiber Laser Advantages

Fiber lasers, compared with traditional optical sources, bring many advantages as a consequence of their unique design:

- Increased flexibility in processing set-up.

The beam quality of a laser is defined by its M2 value, which is determined by wavelength, beam waist radius and far-field divergence, The highest beam quality lasers will have M2 close to 1. This is sometimes referred to as diffraction limited performance, and is a fundamental physical limit. The long thin gain media of fiber lasers lend themselves to producing these high quality beams. Commercially available lasers are available up to a few kW with these high quality beams.
Such beams can be focussed to a very small spot on the workpiece, giving very high power density, which often leads to faster processing. They offer longer focal length (working distance) and greater depth of focus (work-piece positioning tolerance) than competing technologies. For a fixed focal length and focus spot size, the beam diameter as delivered directly from the laser can be smaller. This allows the use of cheaper, lighter process optics that are easier to control about the work-piece. Thus the high beam quality gives a much larger area of parameter space in which to optimise the optical parameters for a particular process. Alternatively, the system can be optimised to achieve the smallest focal-spot diameter, making it possible to process materials in much finer detail than with other lasers. Medical angioplasty stents and solder screen have been manufactured using this property of the fiber laser.

- Reduced Cost of ownership

The high efficiency of the pump source and of extraction from the gain medium produces a very high wall plug efficiency for the laser, typically around 25-30%. This leads to reduced

electrical supply requirements, lower operating costs, a compact laser head and reduced cooling requirements.
Compared to other solid state lasers fewer mechanical components are needed in the laser construction. This leads to significantly lower cost than equivalent power solid state lasers. Indications are that as the pump laser diode prices continue to decrease with increasing manufacturing volumes, that the fiber laser will also become directly cost competitive with kW class CO2 lasers as used in many cutting applications.

- High uptime levels

The laser diode pump sources used for many commercial fiber lasers use technology already developed from the optical fibre telecommunications industry and have extremely high, proven reliability.
In addition the routine maintenance requirements are very low. The all fibre construction means that no alignment of resonator or beam delivery optics are required. The sealed nature of the beam path within the fibre, means that damage due to contamination of optical surfaces will not be an issue.

- Ease of beam delivery

As the light is generated in the fiber, it can easily be delivered to the work piece within a fibre. This provides a very stable set-up, and removes the issues of having to maintain alignment on a number of beam delivery mirrors, or any issues of coupling the laser beam into a beam delivery fibre.

Defense and Space Applications of Fiber Lasers

Fiber lasers are ideal for many defense applications, ranging from tactical and long range directed energy applications to LIDAR to free-space communications. Broadband singlemode and multimode lasers, as well as narrowline, high power amplifiers for beam combining can be employed for directed energy applications.

The Naval Research Laboratory in the USA is developing fiber short pulse systems in the mid-IR as pump sources for generating IR supercontinuum in specialty optical fibers.

Fiber lasers can be used also for spectroscopic remote sensing. A Raman amplifier using fibers with longitudinally varying cores with approximately 3.0W of a 1.26m narrow linewidth continuous wave signal has been demonstrated for remote sensing of atmospheric oxygen levels.

Fiber Lasers find application also for underwater, airborne and space LIDAR applications. In fact fiber lasers merged with state-of-the-art electronics, modulation schemes and algorithms, allow control of the optical wave in time, frequency, polarization, coherence, and spatial domain. Such laser sensors enable advanced remote-sensing capability for military, aerospace and space application.

Industrial Applications and Material Processing

Lasers are the most versatile sources for materials processing. The flexibility to process wide range of materials and the advantages of using lasers over other conventional processes have made lasers the preferred choice for many material processing applications, from cutting cardiovascular stents to drilling of guide vanes in aerospace industry to welding of thick steel for ship building industry.
Single-mode lasers with M2 ▯▯ 1 are better suited for micro as well macro machining due to their ability to focus to the smallest of the spot sizes. The huge power densities associated with the small spot and good beam produce excellent cuts in thin and thick metals for cutting and deep penetrations for welding applications. Scribing, thin film removal for flat panel displays, thin sheet welding are few examples to mention.
Multi-mode lasers offers scalability of powers up to tens kilowatts, while still maintaining a very good beam quality. The wide range of applications with these lasers include cutting of thick automotive hydro form tubes, brazing of auto roof lines, heat treat industrial components, welding titanium panel for aerospace industry, clean cutting of thick stainless steels and aluminum and steel industries.
Nowadays high power femtosecond fiber amplifiers for Industrial Applications are gain increasing interest in industrial applications due to their universality and outstanding machining quality. Increasing demand on microelectronics industry for personal mobile devices is possible by industrial femtosecond laser processing.

To summarize, the main process advantages of fiber lasers are:

- The single mode fibre only carries a TEM00 output giving an M2 of 1.1 or less
- The output power is highly stable across a wide environmental temperature range at +/- 0.5%
- The laser gives fibre delivery via a small beam delivery optic outputting a 5mm collimated laser beam into the focussing optics of the welding head.
- The pumping scheme requires no maintenance, enabling greater uptime and eliminating consumable materials costs.
- The lack of thermal lensing ensures the lasers cannot drift out of calibration or vary in output power with time
- ▯The lack of optical parts ensures no alignment drift with time or vibration.

The number of fiber laser industrial application is very huge. In the following we will recall some of the most relevant and promising.
For many years the most commonly used laser source for industrial metal cutting has been the CO_2 laser. For robot cutting applications the optical requirements for delivery of the free space beam to the workpiece result in complex and expensive optical solutions. The alternative of a fiber laser can offer not only a more elegant engineered solution, but also benefits in terms of performance and cost. The low capital and operational cost of a medium powered fiber laser, when combined with robot delivery, offers users a truly flexible tool for cutting 3-D.

Non-metallic cutting with a pulsed laser. Although more typically used for marking, nanosecond pulsed fiber lasers are ideally suited to cutting a surprising range of materials. They are low cost, compact, reliable and require no maintenance. The scanner based cutting process can be applied to a wide variety of non-metallic materials including ceramics, polymers and even carbon composites, as well as metals. The short pulses and relatively high peak powers that can be achieved with directly modulated seed MOPA designs enable these lasers to be effective cutting tools. As an alternative to standard cw type cutting the pulsed fiber laser can be used in a multi pass vaporisation type cutting process using a scanner to repeatedly pass over the cut line removing a small amount of material per pass. No nozzle or assist gas is required. This technique offers a flexible, accurate and very affordable solution. The cutting speeds that can be achieved varies quite considerably from >10 m/min for thin sections to <10mm/min for thick >1mm materials. The pulsed laser can also be used to cut a wide range of non metallic materials such as plastics and even rubbers. A key factor in determining if a material can be cut is the level of the absorption of the material to 1µm laser light. Many plastics have high transmission at this wavelength and are therefore not suitable, however, some materials can be cut. The use of IR absorbing additives to many polymers is becoming a more common place solution particularly for marking and in some cases these additives may enhance cutting. Some materials such as certain polyester and polyethylene can be cut but tests should be made to assess suitability. Rapid prototyping is one of the processes that are grouped under the general heading of Additive Manufacturing. Other processes available under this heading are Layer manufacturing or Solid freeform fabrication (SFF) processes. This process has initially been used in product development and is now starting to be deployed in rapid manufacturing. Many rapid manufacturing processes use industrial lasers as an energy source. Fiber lasers are particularly suitable for metal processes. The major attributes of the industrial fiber laser that make it particularly suitable for this range of applications are the continuous wave nature of the laser beam and high modulation speed, the stability of the fiber laser, the focus-ability, and no thermal lensing. In fact the ability of the fiber laser to produce square pulse shapes with a fast turn-on time and with continuously variable pulse lengths make it an ideal source for scanner based systems. The stability of the fiber laser is typically +/- 0.5% of output power and it is unmatched by conventional solid state lasers and leads to a stable sintering process. Moreover the high beam quality of the fiber laser enables focussed spot sizes of 30 - 50 microns to be achieved with long focal length lenses. These small spots allow finer detail and lighter structures to be produced. Finally thermal lensing, the increase of focused spot size with changing laser pump power, has plagued solid state laser designers for many years. When a 9.5 mm diameter glass laser rod is pumped with up to 10 kWs of flash lamp pump power, thermal gradients created in the rod cause optical distortions in the beam. In the case of the fiber laser, fiber coupled diode pumping and a very thin, long fiber laser resonator make it simple to maintain lasing at close to ambient temperature simply by conduction cooling.

Fiber laser can been successfully used also for welding of fuel cells. The range of applications for fuel cells is extensive. They can be used for consumer electronic devices, residential power generation, the automotive industry and industrial power generation. There are a number of welding applications within a fuel cell that a fiber laser can be used for: bi-polar plates, reformers, fuel processors, heat exchangers. The important point on all of these applications is that they all require high speed and high quality welding of thin stainless steel sheets with low distortion. This is an application at which fiber lasers excel and hence this application will inevitably be served predominantly by fiber lasers.

Medical Industry Applications

As the medical industry continues to demand smaller and more intricate components and devices, so the challenge for manufacturing them increases. The performance advantages of fiber lasers over conventional technologies in terms of beam quality, depth of focus and parametric dynamic performances have been well recognized. Coupled with the benefits in wall plug efficiency, process versatility, reliability and cost have led to an increasing level of deployment in medical device manufacturing in both fine cutting and micro welding applications. Laser welding has become an established technology in medical device manufacturing due to the following key advantages: process repeatability, in fact laser welding is a non-contact process which eliminates potential problems caused by wearing parts, contact deformation or contamination; process control, the high beam quality and a resulting spot size control together with the continuously tunable average power of a fiber laser ensure that the weld energy is delivered only where it is needed and with exceptional control; hermeticity, unlike soldering or brazing, laser welding can provide high quality hermetic welds with high yield, both of which are fundamental requirements in the manufacturing of high value implantable medical devices; surface finish, in addition to the aesthetic quality, the smooth and pore-free surface finish achievable enables reliable autoclave sterilization.

Of special concern to the medical industry is the need to laser welding of clear or light - coloured plastics. High brightness lasers are normally employed for applications where very high power density is required i.e. metal cutting. In this case, power densities in the order of 20 MW/cm2 are required. In the case of plastics welding, typical power densities are several orders of magnitude less, ~ 100-300 W/cm2. Plastics are normally welded using a transmission welding technique where one component of the joint is transmissive and one is absorptive for the laser wavelength used. In this way, controlled melting or wetting occurs at the joint interface. Plastics welded by conventional thermal welding techniques can also be laser welded. Specialised plastics are now becoming available that appear black but transmit enough of the laser beam to allow them to be used as the upper component of a transmission welded joint. The absorbing component of the joint usually contains carbon which is of course a very efficient absorber of IR radiation.

Laser cutting of very thin walled tubes (stents) has developed rapidly in line with demands from the medical device industry. It is possible to laser cut extremely complex shapes in 2 mm diameter tubes with walls as thin as 0.2 mm. The average power required for these small scale tube cutting applications is in most cases relatively low, with most stainless steel stents typically being cut with 50-100W rated fiber lasers, with higher power levels needed only for nitinol. Certain specialist manufacturers now offer fully integrated laser cutting systems commercially fitted or retro-fitted with fiber lasers. These systems provide the sophisticated clamping and high accuracy multi-axis movement required for precision cutting of a range of different medical device materials.

As the medical industry continues to demand smaller and more intricate components and devices, so the challenge for manufacturing them increases.
Fine wire welding is used in the manufacture of a wide range of medical devices ranging from electrical connections to implantable medical devices; vascular stents and guide wires used in minimally invasive medical applications to position devices such as catheters and stents. Thus fiber laser can be applied in butt welding of titanium, stainless steel, stents and guidewires, as well as lap and spot welding of stainless steels and titanium wires. Fine wire geometries are typically in the range 100-300μm in diameter and include materials such as stainless steel, cobalt chrome, platinum chrome, nitinol, titanium, molybdenum, tungsten, magnesium and platinum. Applications examples include bonding parts of both identical and dissimilar geometry and material composition.
It is worth noting that when different materials are being welded the different melting points and thermal conductivities often require careful selection of the laser processing parameters and a very high level of process control in order to achieve a successful joint. Laser welding of fine wires can be achieved in a number of ways including butt welds (when wanting to weld two wires together) and lap welds (often used to join adjacent wires). Spot welding can be also used when joining a wire to another part or component.

Medical and Aesthetic Applications

Medical laser systems market is expanding at a steady rate worldwide. Currently, lasers are being extensively employed for diagnosis and treatment of a number of diseases, which hitherto were difficult to treat using traditional medicine. Lasers now offer wide applications in ophthalmology, oncology, cosmetic surgery, cardiology, dentistry, gynecology, dermatology, gastroenterology, diagnostics, and urology. They form an important part of several medical equipments currently available in the market. Lasers required for cosmetic surgery such as skin resurfacing, tattoo and hair removal among others are very popular, especially in developed countries. Electrosurgery is emerging as an exciting prospect for surgeons. Dental lasers market is expected to witness a significant increase in the next few years. Lasers sales are being driven by significant growth in hair removal procedures. Use of lasers in the treatment of skin wrinkles is increasing, driving the overall aesthetic lasers market. Rapid developments in fiber-laser technology are likely to create new potential avenues for its use in medicine and surgical applications in the coming years.
Surgical laser represents the largest segment accounting for a major share of the global medical laser systems market. Diagnostic lasers segment is projected to lead the medical laser systems market with the highest growth rate compounded through 2015.
For surgical applications it is important that the laser be compact, low maintenance, and efficient. The high efficiency and good thermal management of fiber lasers make them very

suitable for surgical applications, and because they are diode-pumped, they are also compact. The fiber geometry has an additional advantage over bulk solid-state lasers because it alleviates the need for an additional delivery fiber, thus reducing cost and system complexity.

Some research groups and commercial entities are pursuing lower-power fiber-laser applications in medicine, such as optical coherence tomography (OCT), microsurgery, and skin resurfacing. In fact, fiber lasers will increasingly replace more-established light sources in medical applications, thanks to their lower cost, inherent user-friendliness, broad range of energy delivery (pulsed and continuous wave), and applicability for both surgery and diagnostic imaging.

Other Applications

Pulsed fiber laser systems are under development at Lawrence Livermore National Laboratory (USA) as photo-cathode drive lasers for linear accelerators and injection seed lasers.

High power cw lasers can be used also to generate ultrasonic wavefronts in materials. Upon detection, these wavefronts provide a new and rapid method of determining strength and defects where contact ultrasound transducers cannot be used.

An ultrafast, fiber-based laser fabrication system has been developed at Los Alamos National Laboratory, USA. This system has been used for many applications including THz metamaterials, waveguides, microfluidic devices, and fiber Bragg grating Sensors.

Recently JHU Applied Physics Laboratory (USA) demonstrated that dual-wavelength fiber lasers using stimulated Brillouin scattering gain offer unique capabilities for a variety of microwave photonic applications, including millimeter-wave frequency synthesis, communications, and generation of low-phase-noise signals.

The total laser revenues expectations are that in the following year fiber laser will expand in each of these applications.

Market

According to the Laser Focus Word Annual Review And Forecast, the laser markets survived the big one the global economic recession of 2008/2009 and recovered nearly all their losses by the close of 2010. By all measures, 2010 and early 2011 were more favorable for laser manufacturers than anyone could have predicted. But just in the last quarter of 2011, orders began slipping out for some customers, and worldwide stock markets continued their wild vacillation on alternating good- and bad-news reports surrounding the European sovereign debt crisis and a possible slowdown in China.

Worldwide laser sales reached $7.46 billion dollars in 2011, growing 14% compared to 2010□□3% higher than our 11% growth forecast last year. But for 2012, Laser Focus Word see aftershocks from the great recession continuing for a while longer, with negative news stories hopefully balanced by a continuing increase in personal electronics sales, as well as growth in manufacturing cost-reduction and automation strategies that welcome more machine-vision and laser tools. For 2012, Laser Focus World forecasts laser sales to grow a modest 1.2% to $7.57 billion.

Industrial laser revenues in 2011 came close to the magic $2 billion level showing a 19% increase over the previous year. Carbon-dioxide (14%), solid-state (4%), and fiber laser (48%) sales increases were joined by a 17% growth in sales of diode and excimer lasers (grouped in the ��other materials processing�� category). A modest forecasted 5% growth will vault industrial laser sales above $2 billion in 2012.
Laser system revenues in 2011 tracked laser numbers and are estimated to set a new high with a significant 16% increase over the previous year. A strong rebound in the sheet-metal-cutting market is the main contributor to this record-setting performance as both high-power CO_2 and fiber lasers pushed unit sales up more than 15% over 2010. This market sector dominates system revenues with more than half the 2011 total.
Metal processing continues to lead laser application revenues at 68% of all units sold. This is followed by marking/engraving systems at 17% and microprocessing at 8%. Other applications grouped totals 7%. On a unit basis, marking /engraving accounts for 59% of all industrial lasers sold even though revenues do not top $332 million in 2011.

The laser market for medical (ophthalmic, surgical) and aesthetic (wrinkle and hair removal, liposuction, skin resurfacing) applications continues to grow steadily. Revenues in this segment are expected to reach $518 million in 2012, 3.9% growth compared to 2011.
While solid-state lasers still comprise the lion��s share of the total laser revenues in the medical and aesthetic laser category, laser diodes garner 13% of the total and represent by far the largest number of units (hundreds of thousands of diodes compared with thousands of lamp-pumped solid-state lasers, for example, in 2011). New entrants such as femtosecond lasers are being researched by companies including Carl Zeiss Meditec (Dublin, CA), Abbott Medical Optics (AMO; Santa Ana, CA), and OptiMedica (Santa Clara, CA), to replace excimer lasers in both corneal incision and vision correction, and for cataract surgery, respectively, owing to reduced cavitation bubbles and thermal damage.
Much more detail on the laser markets is available from Strategies Unlimited in its recent report, Worldwide Market for Lasers 2012 (www.strategies-u.com).

Conclusion

Fiber lasers are proving to be a versatile and robust technology offering outstanding performance, scalable output power, and extended wavelength coverage. They have enhanced existing applications and are enabling new ones progressively increasing their market share.

We would like to conclude this document with a recent history of success in the fiber laser word. At the end of June 2012 the 2 micron high-power mode-locked fiber laser from AdValue Photonics has been selected as a winner of the 2012 R&D 100 Awards. Widely recognized as the "Oscars of Innovation", the R&D 100 Awards identify and celebrate the top 100 high-technology products of the year as defined by R&D Magazine. The AdValue Photonics winner is an all-optical-fiber laser with no free-space components in the optical system, providing advantages in operation stability and reliability. With a 2 micron wavelength, picosecond pulse width, 10 kW peak power, and near-diffraction-limited beam.

This fiber laser is a tool for scientists working with nonlinear optics, frequency conversion, spectroscopy, light detection and ranging (LIDAR), and materials studies.

Fiber laser applications encompass many industries from commercial to military, and for applications spanning environmental monitoring, industrial process control, hazardous chemical detection, molecular identification, thermal imaging, materials processing, and medical diagnostics.
The know-how on fiber laser developed by each partner in the framework of the ALPINE project will surely find application besides laser scribing.

List of Websites:
http://www.project-alpine.eu
Coordinator and all WP leader contact details are available on the Alpine web site.