Il Progetto Europeo ALPINE

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Advanced Lasers for Photovoltaic INdustrial processing Enhancement

EU-FP7 - Large scale integrating project funded by the **European Community**
Work Programme:
Nanosciences, Nanotechnologies, Materials and New Production Technologies
Budget: **9.1 M€**
Duration: **3 years**
15 Partners

Alpine Partners

University of Parma
Italy

NKT Photonics A/S
Denmark

Solar Systems & Equipment
Italy

Würth Solar GmbH & Co.
Germany

Oclaro
Switzerland

Quanta System S.p.A.
Italy

NEXCIS
France

University di Verona
Italy

European Commission Joint Research Centre
Belgium

EOLITE Systems
France

Univerza v Ljubljani

University of Ljubljana
Slovenia

Elettrosystem SAS
Italy

MULTITEL
Belgium

Zentrum für Sonnenenergie-und Wasserstoff-Forschung
Germany

LPKF Laser & Electronics AG
Germany

Alpine Targets

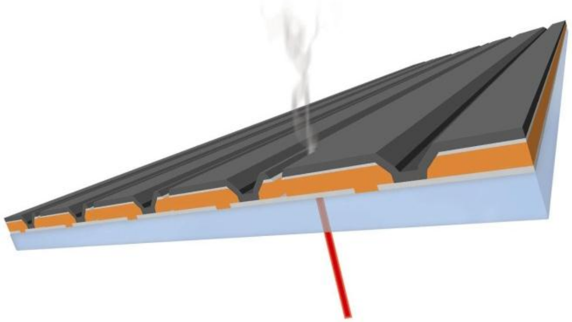
- Development of **fiber laser based on Photonic Crystal Fibers (PCFs)** for the scribing of solar cells.
  MOPA and Q-switched configurations.

- Development of new PV thin films in cadmium telluride (**CdTe**) and copper indium diselenide (**CIS**) or copper indium gallium diselenide (**CIGS**).
  Both technologies on glass and flexible substrate.

- Improvement of the **scribing technique** in terms of accuracy and speed, by substitution of mechanical scribing by **fiber laser scribing**.

Summary

- Scribing of photovoltaics modules
- MOPA and Q-switched fiber laser
- Narrowband seed laser
- Fiber design and manufacturing
- PV module production and evaluation
- Conclusions



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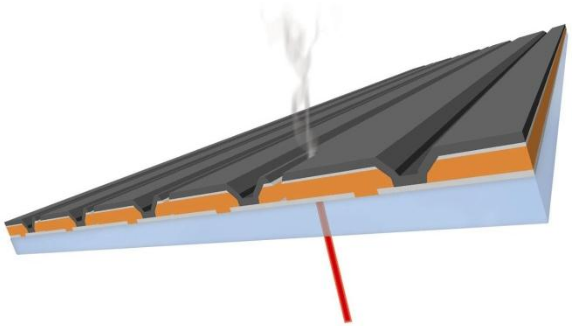
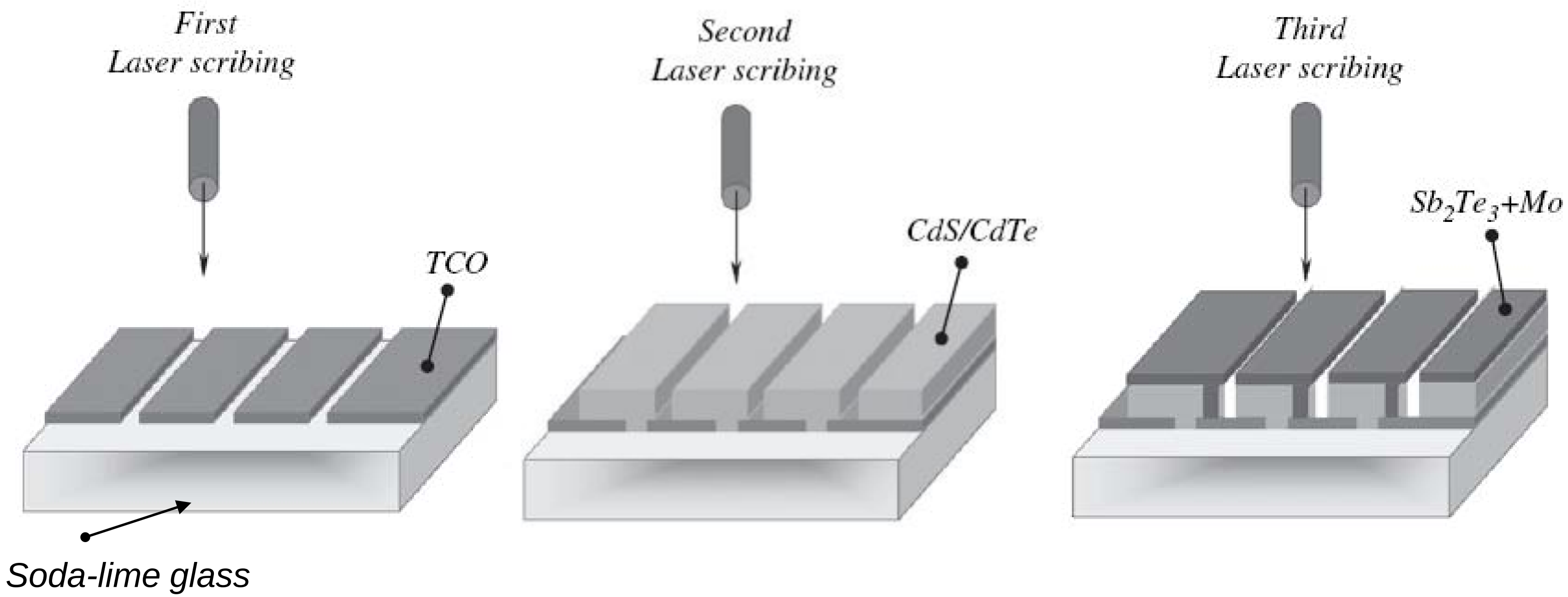


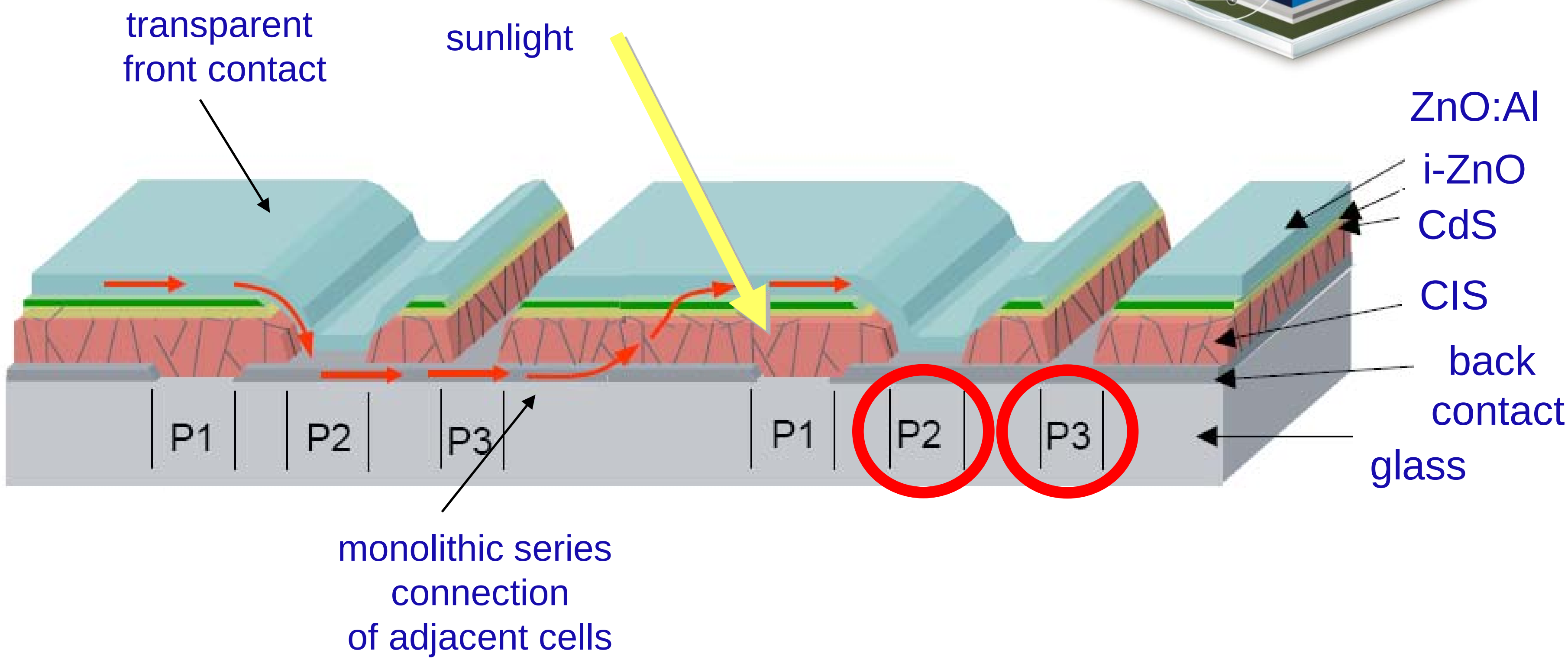
Manufacturing and scribing

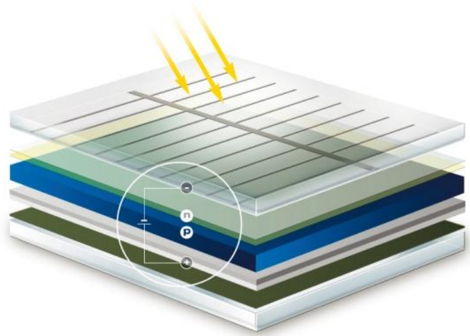


Scribing must be done monolithically during the fabrication of the panel.

Photovoltaic module

Substrate buildup



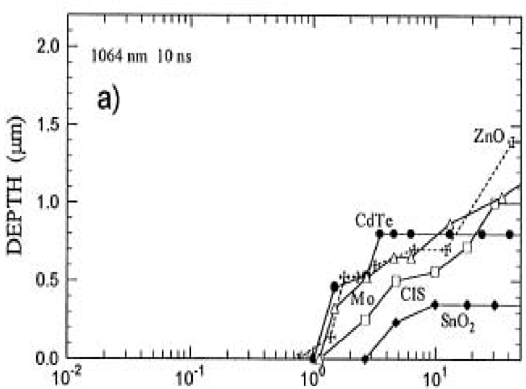


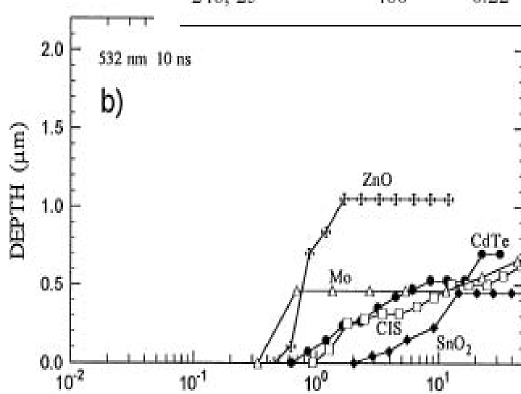
Material properties

- ✓ Material Damage Threshold
- ✓ Scribing depth
- ✓ Material absorption

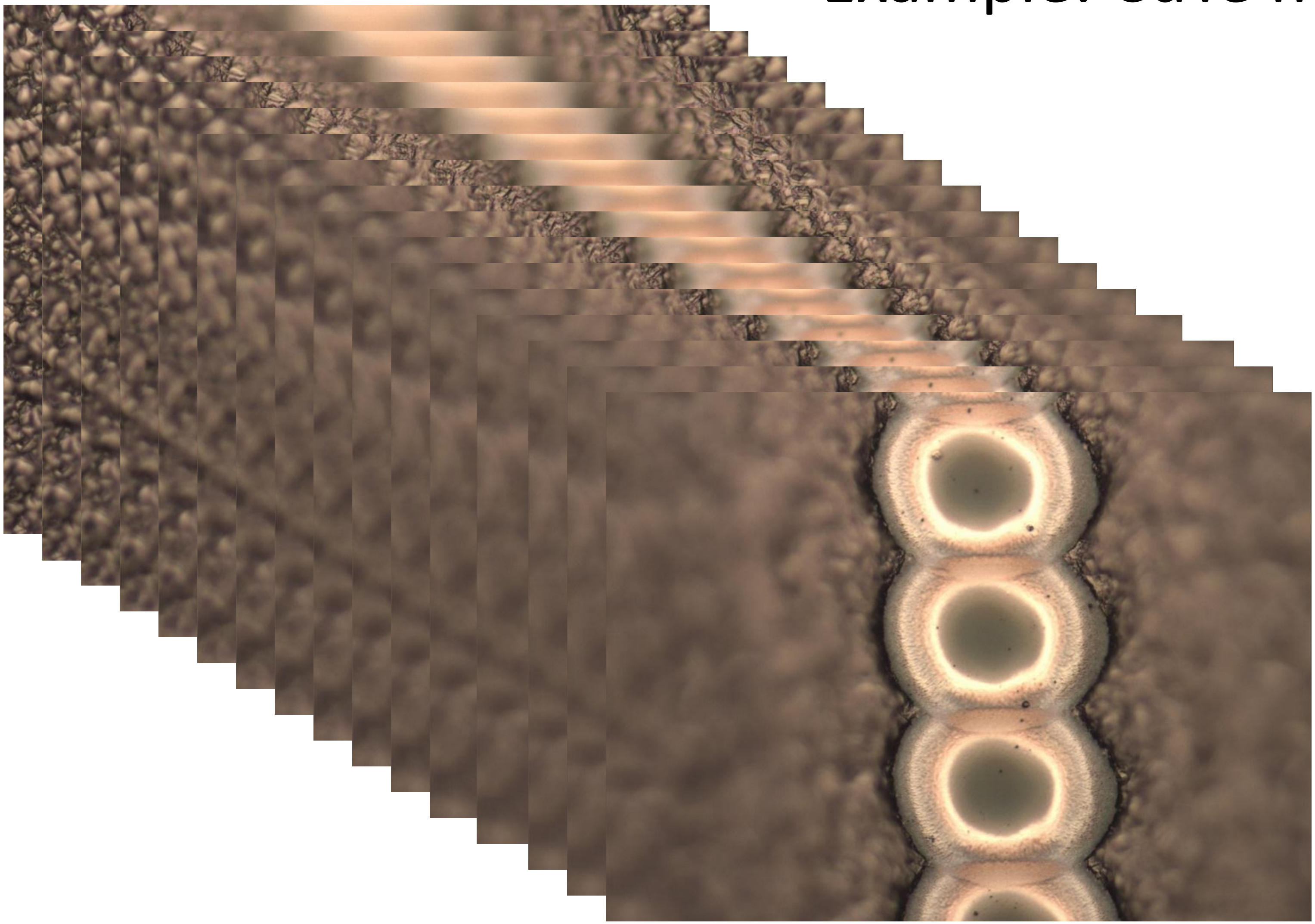
Damage threshold for thin-film materials (J/cm^2)

λ(nm), τ(ns)	E_{max} (mJ)	SnO_2 (J/cm^2)	CdTe (J/cm^2)	Cu/Au (J/cm^2)	ZnO (J/cm^2)	CIGS (J/cm^2)	Moly (J/cm^2)	Si (J/cm^2)
1064, 0.1	1.1	1.8	0.8	0.9	5.8	0.14	0.87	5.8
1064, 250	1.3	2.6	1.1	0.73	6.8	0.14	0.73	6.8
1064, 70	2	4	1.5		7	0.5	1.5	
1064, 10	500	2.4	0.65		3.9[a]	0.32	0.44	
532, 0.1	0.07	1.5	0.016	0.016	3.3	0.028	0.16	1.2
532, 250	0.014	1.6	0.017	0.021	> 2.8	0.021	0.16	1.6
532, 90	2	5	0.22		12[a]	0.23	0.5	
532, 70	1.5	6	0.07		10	0.07	0.7	
532, 8	200	4.5	0.10		3.5[a]	0.15	0.26	
511, 55	2.0	3.4	0.10		0.6	0.1	1.0	
308, 15	80	0.44	0.08		0.24	0.13	0.24	
248, 25	400	0.22	< 0.07		0.16	< 0.08	0.32	

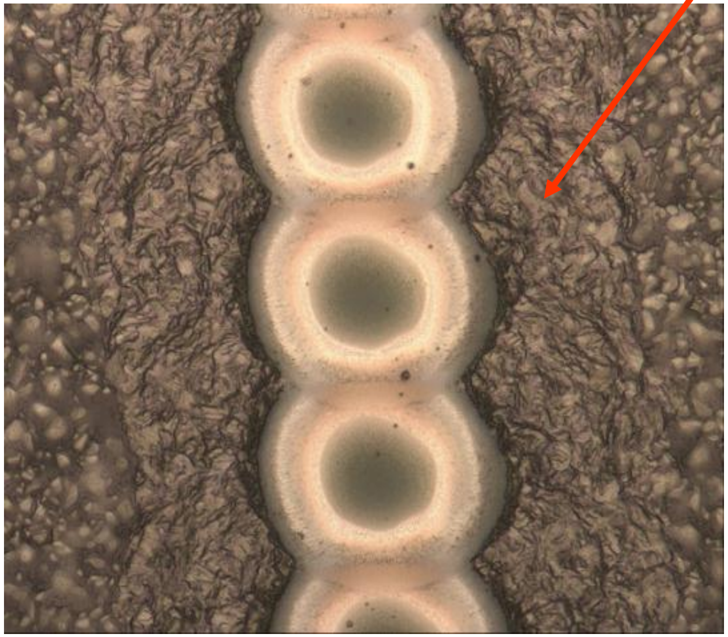




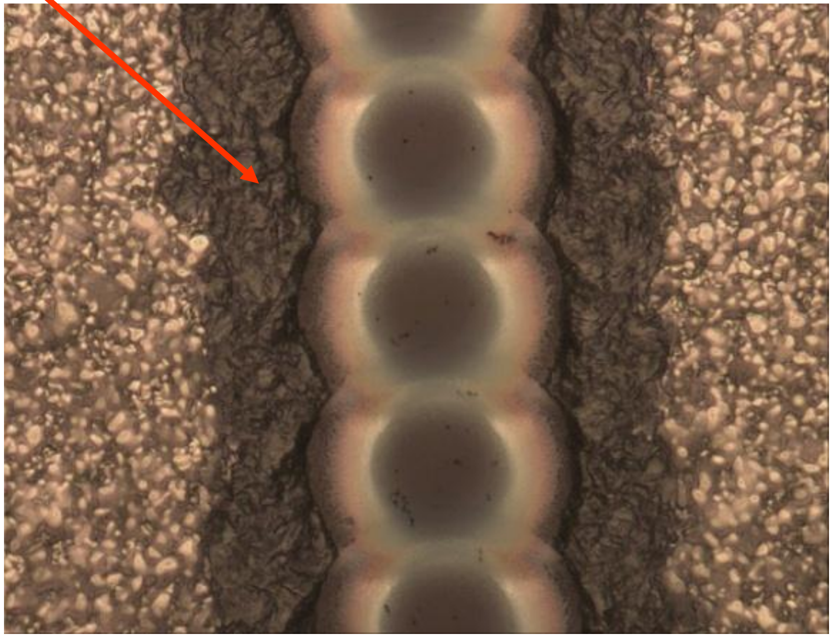
Example: CdTe module



HAZ (Heat Affected Zone)

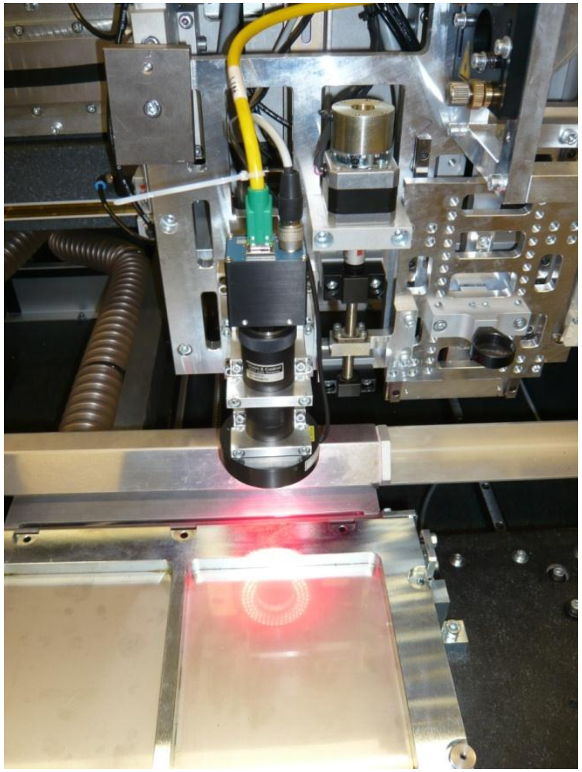


Scribing P_2, RR=32 kHz P=0.4 W



Scribing P_3, RR=35 kHz P=0.5 W

Scribing machine



Scribing machine by **LPKF**, Germany

Summary

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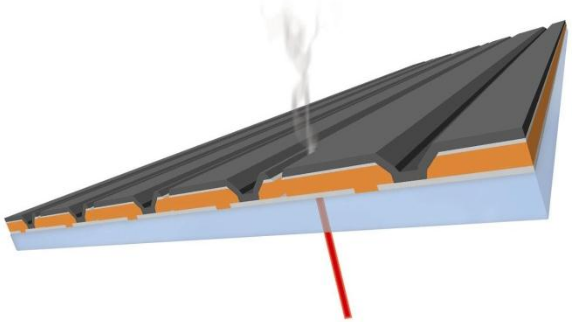
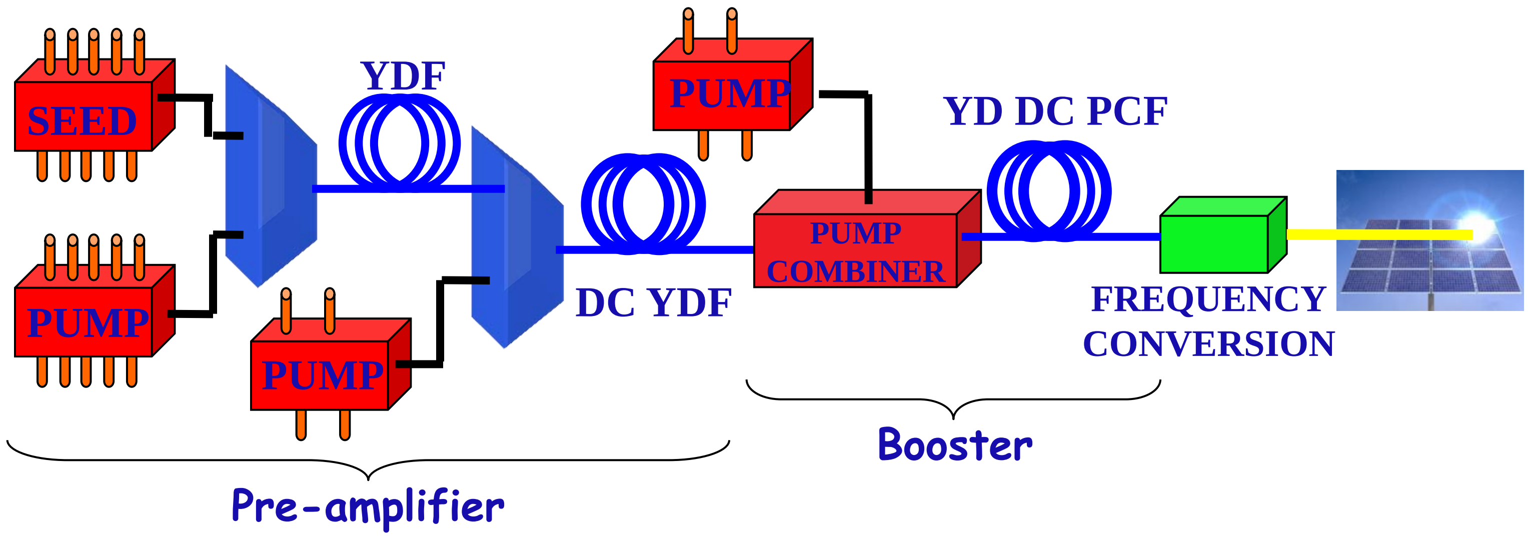
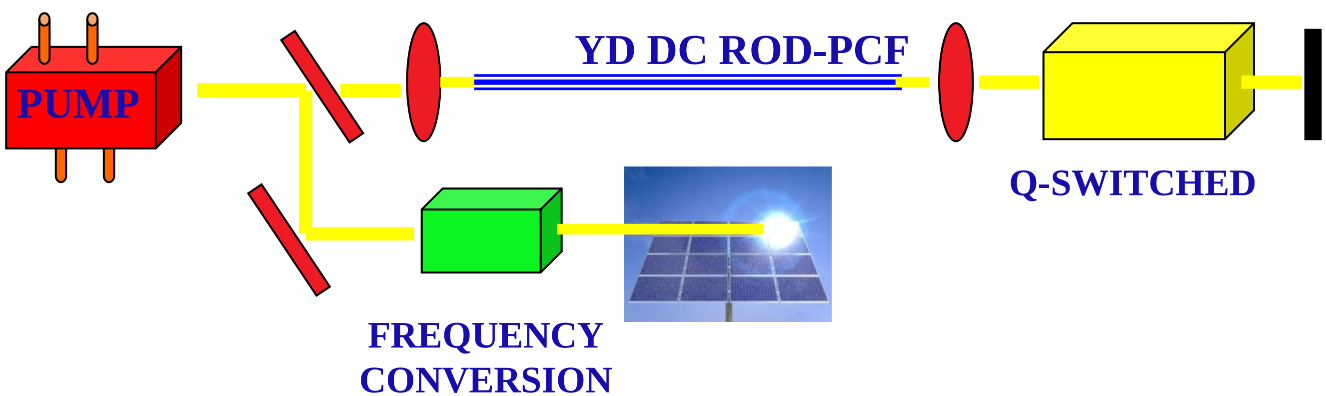


- ✓ Master Oscillator Power Amplifier (MOPA)



- ✓ Q-switched

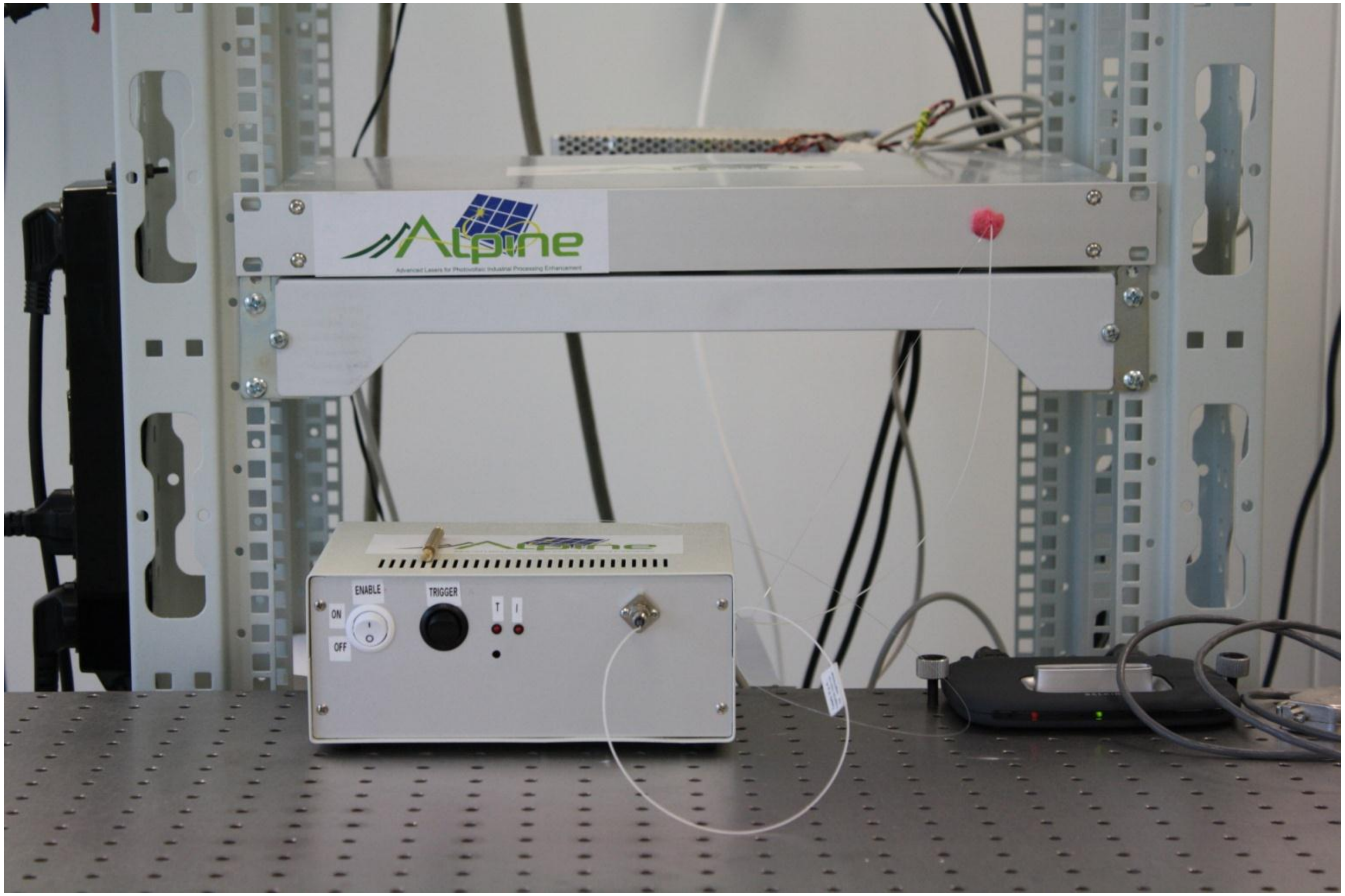


Laser specs

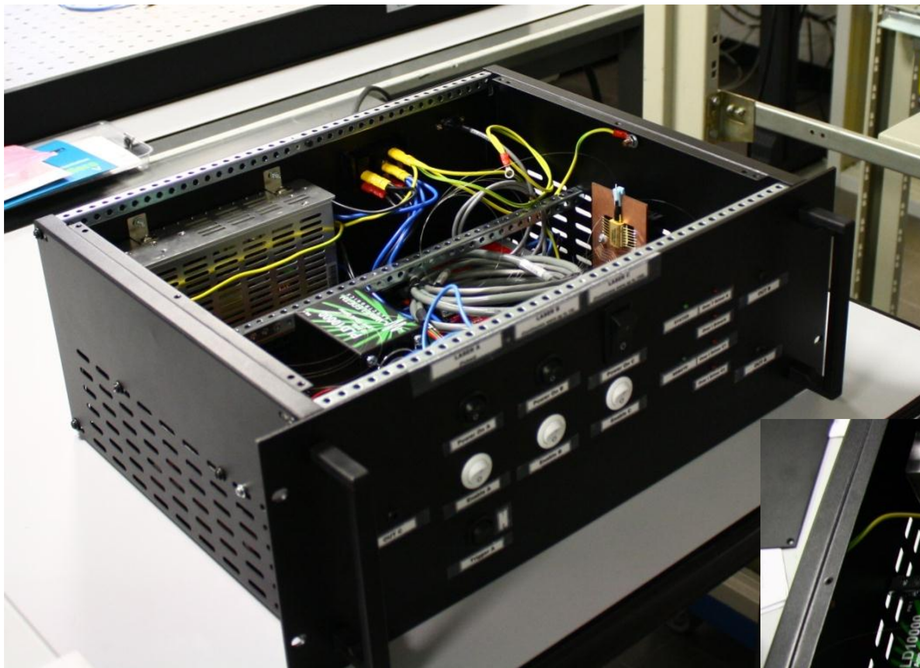
Relevant Specification	Targeted Range
Emission wavelength	IR 1064 nm,1030 nm Green 532 nm, 515 nm UV 355 nm, 343 nm
Pulse repetition rate	10 – 300 kHz
Pulse duration	200 ps – 50 ns
Mean power (IR)	>100 W
Mean power (green)	> 50 W
Mean power (UV)	20 W
Output beam quality M^2	< 1.3

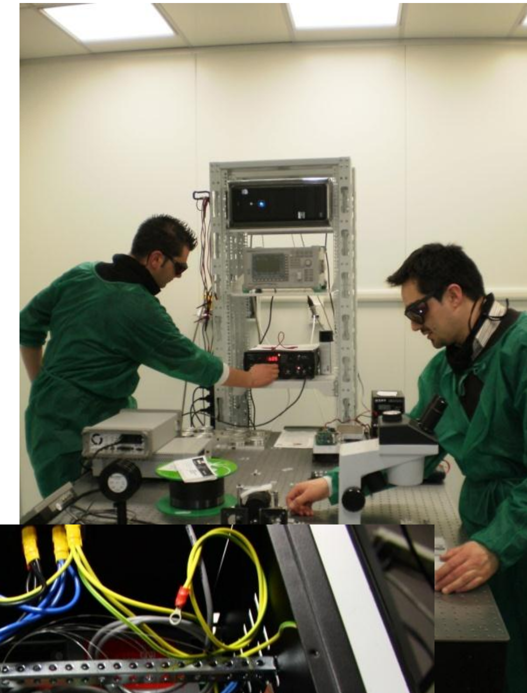
- Several parallel beams used (50-100 lines);
- P1 up to 8W @ 1064 nm;
- P2, P3 1-10 W @ 532, 355nm;

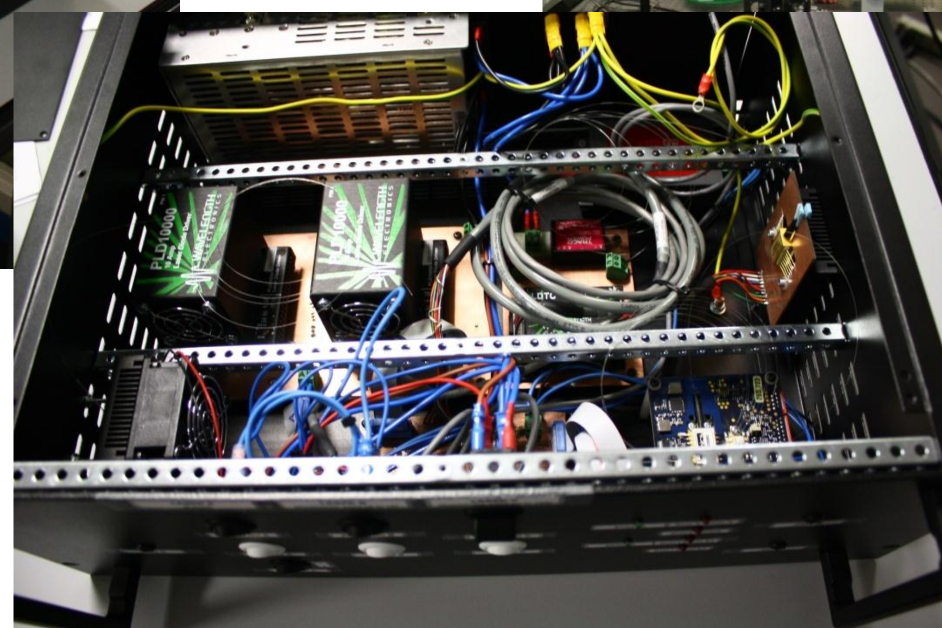
Laser prototype



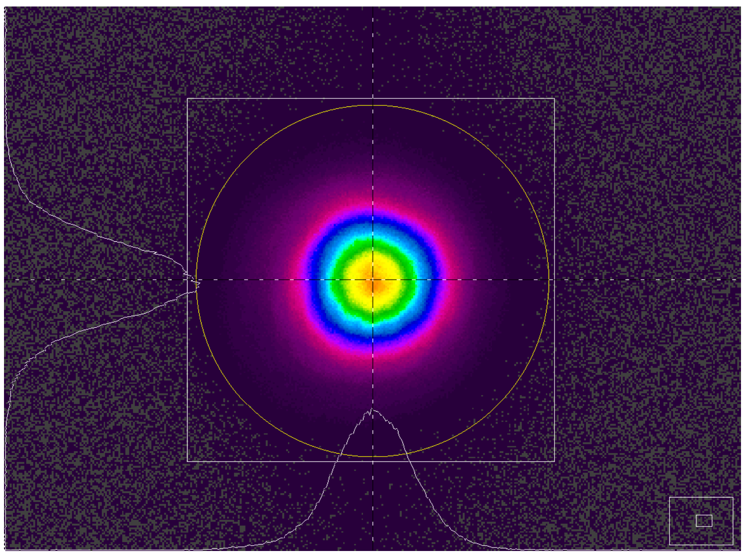
PM laser prototype

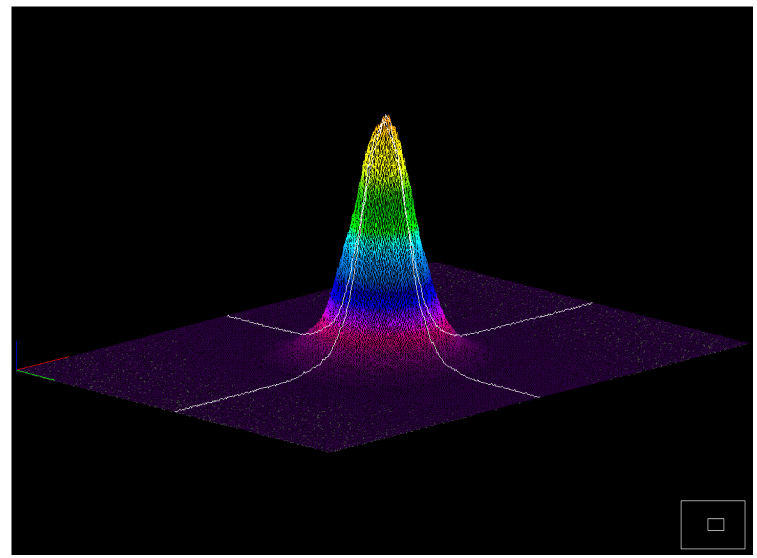






Beam profile

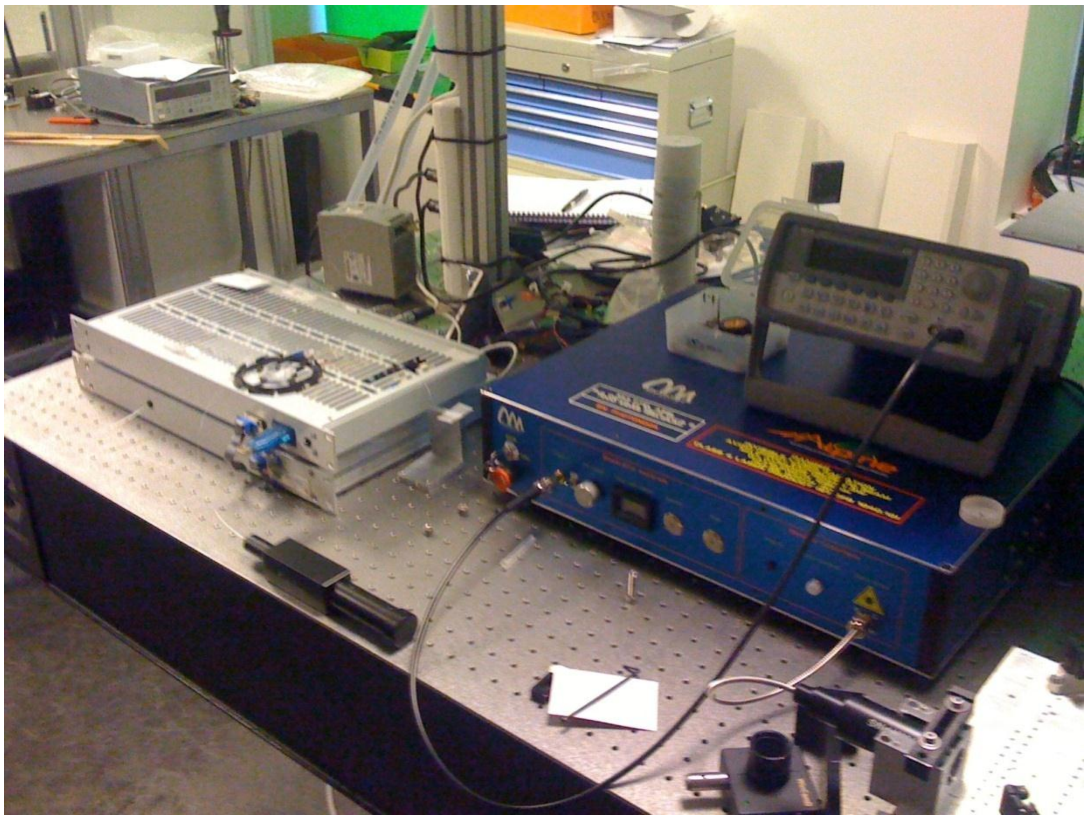




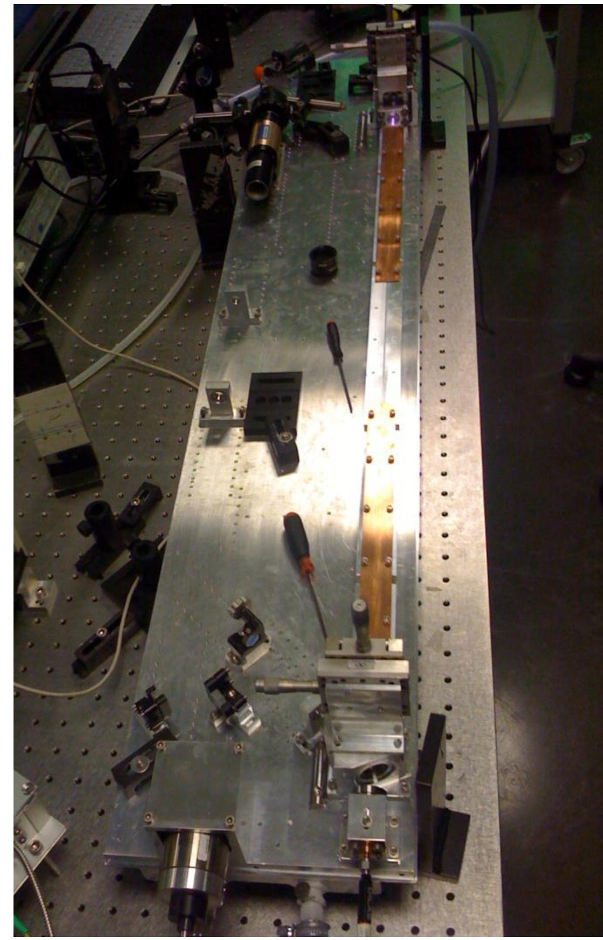
$M^2 = 1.1$

Booster stage

QUANTA Systems MULTITEL



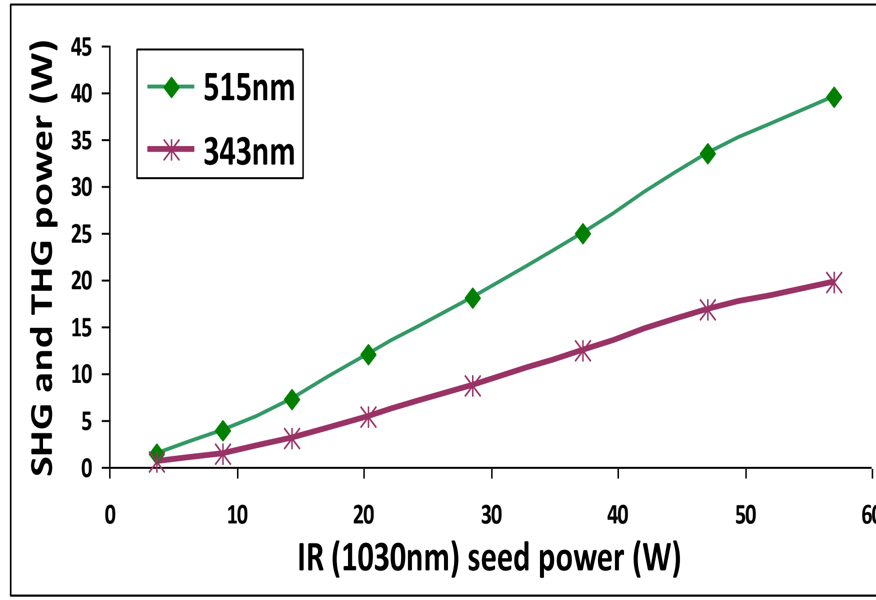
EOLITE

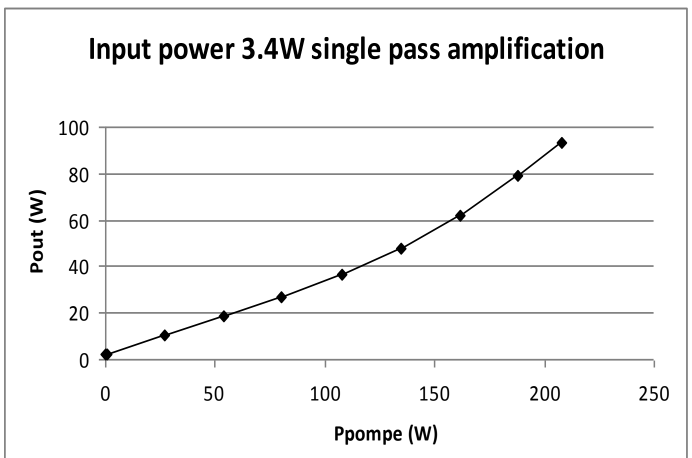


Performances

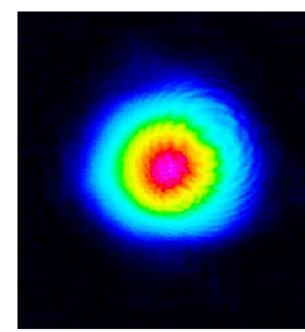
Alpine partners (EOLITE and MULTITEL) have demonstrated, in pulsed regime:

pulse duration of 30 ps at 5,9 MHz
More than 40 Watts at 515nm
Up to 20 Watts in the UV (343nm)
Max efficiency: 70% for SHG
35% at 343nm.



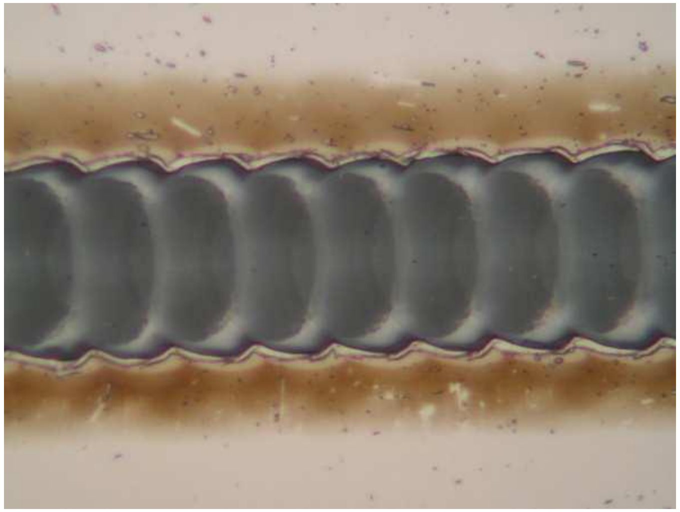


Improvements at 80 MHz 30ps:
3.4 W average seed laser
in a single-pass amplification,
$M^2 < 1.1$, spectral linewidth of 0.12nm.



Requirements for patterning step P1

Groove width	60 - 70 µm
Lateral pulse overlap	≈ 50% - 70%
Pulse duration	≤ 40 ns
Pulse energy (for Mo layer thickness ≈ 300 nm)	≈ 200 µJ
Wavelength	1064 nm

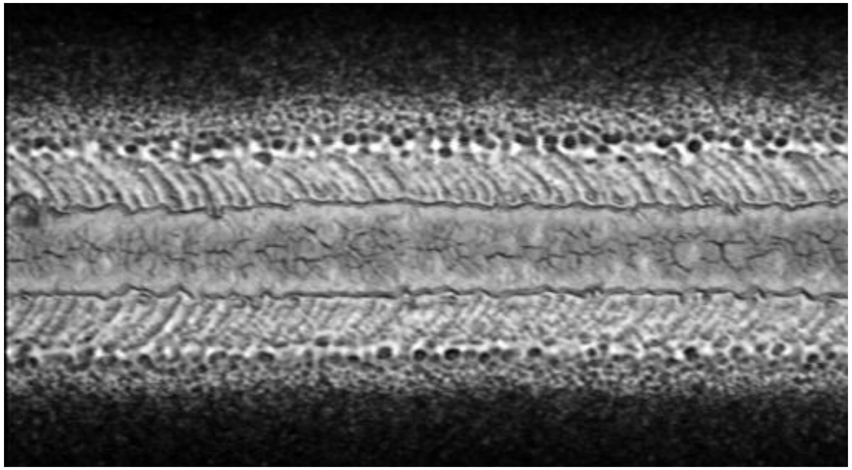


Microscopic image of a P1 scribe in 300 nm Mo on glass

Requirements for patterning step P2

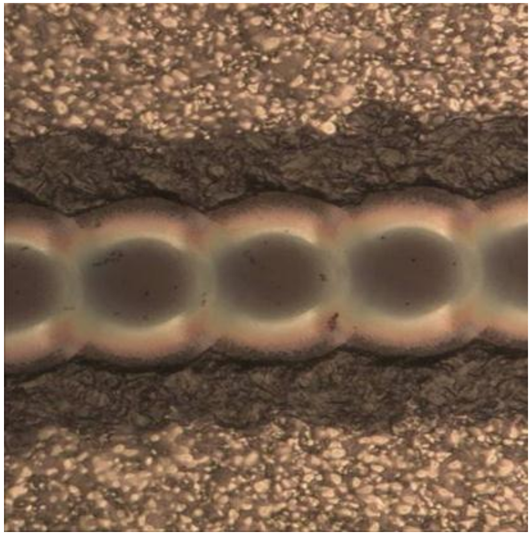
Groove width	≈ 30 µm
Lateral pulse overlap	≈ 50% - 90%
Pulse duration	≤ 10 ns
Pulse energy	≈ 100 µJ
Wavelength	532 nm
Pulse rate	High

P2 scribe in CIGS on Mo/glass



Requirements for patterning step P3

Groove width	few µm
Lateral pulse overlap	≈ 50%
Pulse rate	> 100 kHz
(depending on feed rate and overlap)	
Pulse duration	≤ 100 ps
Pulse energy	a few µJ
Wavelength	355 nm



P3 scribe in CdTe module

Requirements for Edge Cleaning

Spot diameter	0.1 – 1 mm
Lateral pulse overlap	≈ 20% - 70 %
Pulse duration	≤ 40 ns
Pulse energy	≈ 200 µJ
Wavelength	1064 nm

Edge cleaning parameters for large area removal.
The edge cleaning parameters for the removal of the shunted zones are identical to the P3 parameters.

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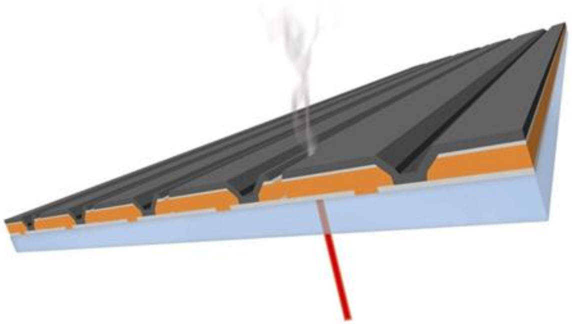


Seed laser

OCLARO has been developed highly **efficient DFB lasers be used as the seed source for MOPA fiber laser** systems.

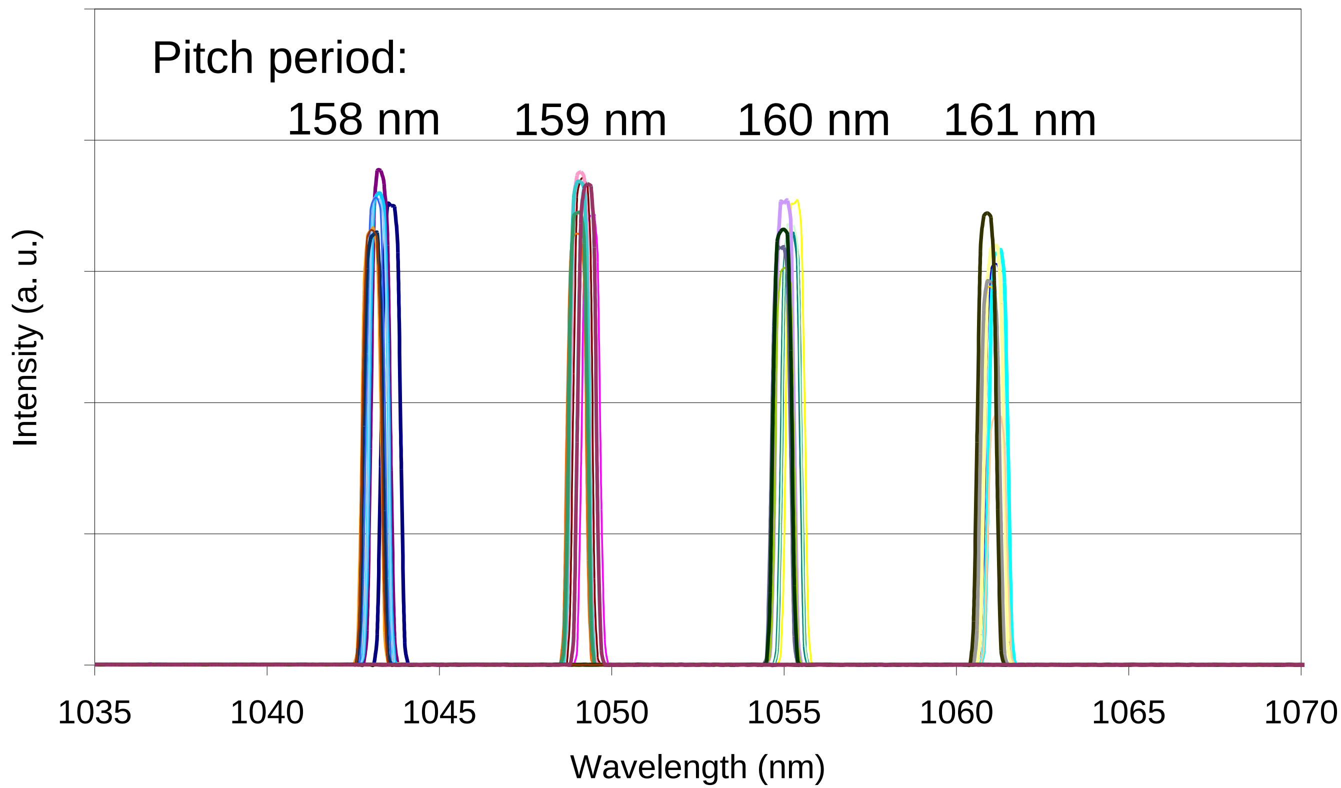
Such DFB lasers are operating in **10xx nm spectral region**, driven in either **CW or pulse regime**.

Since the wavelength selective feedback is located inside of the laser itself, the fast locking is guaranteed by design, and the DFB laser can be modulated with pulses as short as **few 10s of picoseconds**.

The laser epitaxial structure was based on OCLARO's high-power single mode **InGaAs/AlGaAs SQW** laser diodes with the gain maximum adjusted for emission at around 1060 nm.

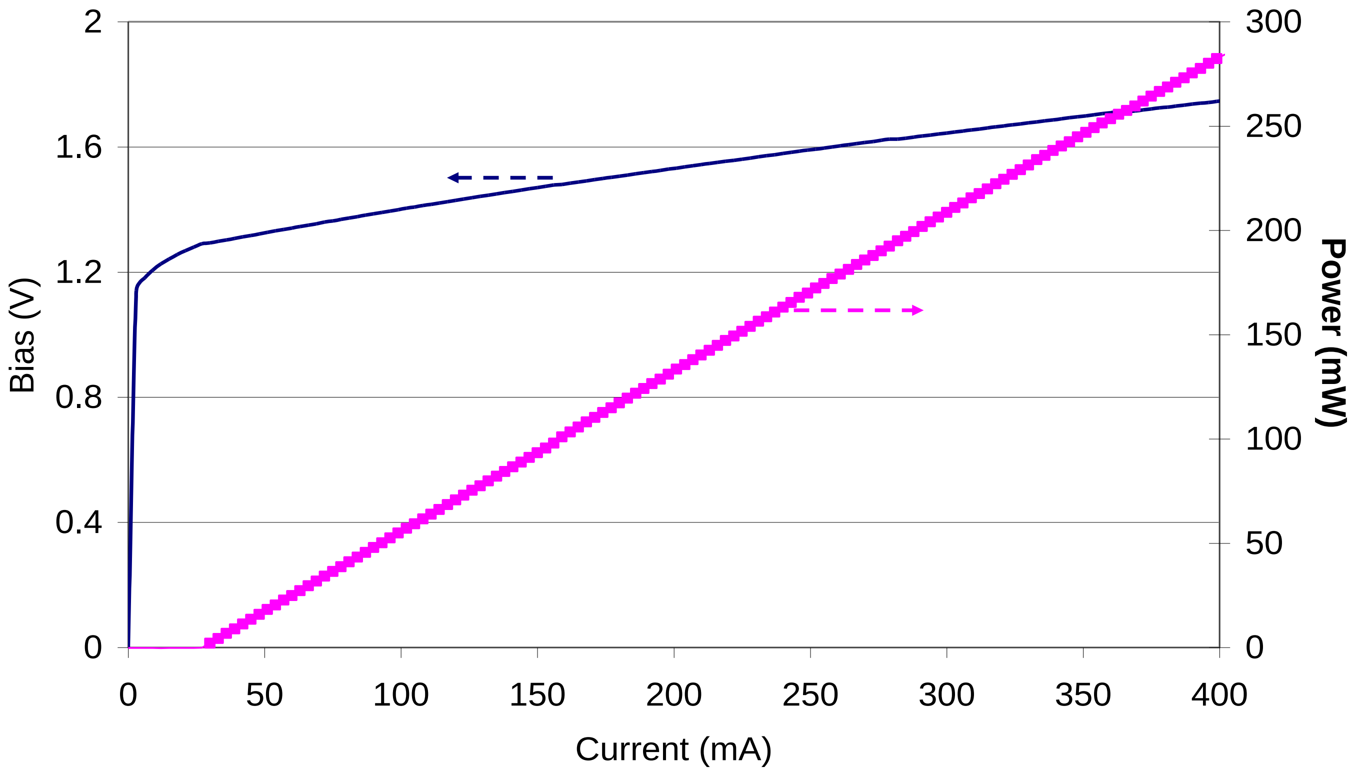
The first order DFB gratings were defined using **e-beam lithography**. Gratings were etched using the **Reactive Ion Etching** kit. After the overgrowth the narrow stripe ridges of ~4.5 µm wide and 1.8 mm long were processed.

Seed laser spectrum



Spectra for the DFB lasers with first order grating and various grating periods measured at room temperature in CW regime.

IV characteristic

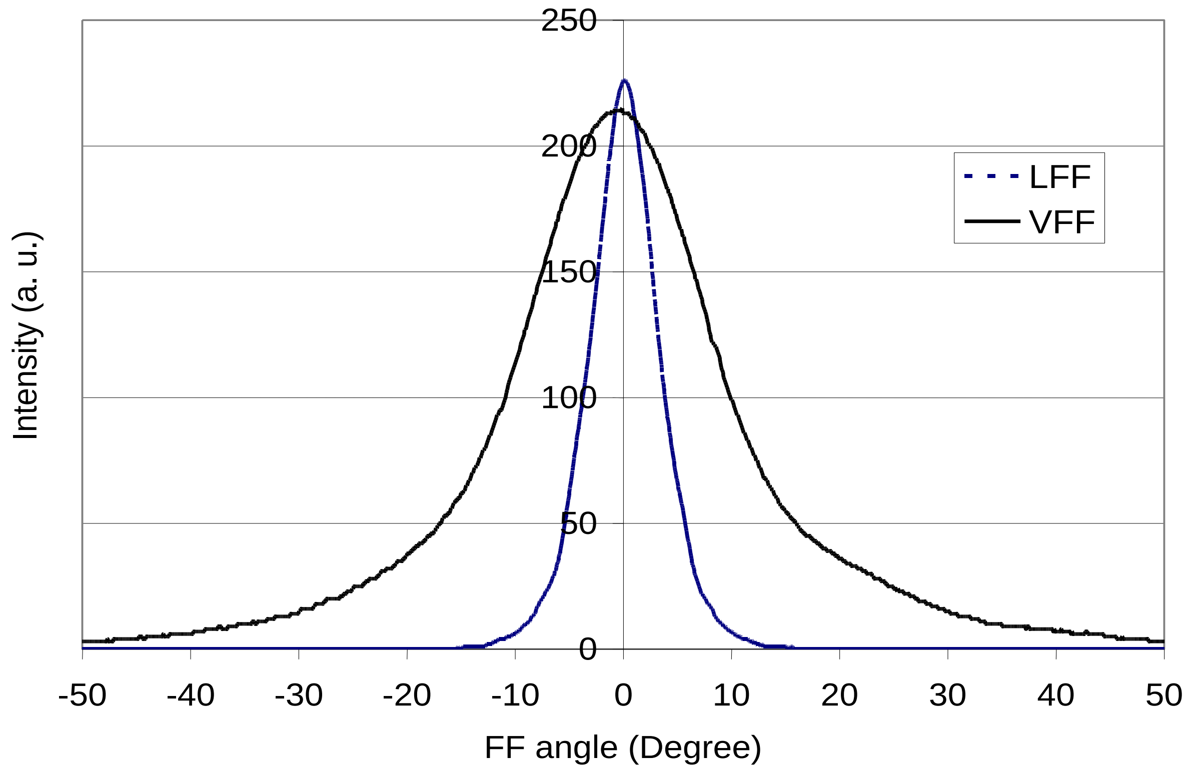


The laser has a threshold current of about 30 mA.

Tested up to maximum current of 400 mA producing ~280 mW power.

The curve is kink free up to maximum drive current.

Lateral and Vertical Far Field



LFF and VFF provide with the evidence that laser is operating in the **single spatial mode regime**.
Spatial single mode is required for the efficient coupling into single mode fiber during the module build.

Fiber coupling experiments have demonstrated that the power out of polarization maintained single mode fiber well exceeds 200 mW at 400 mA.

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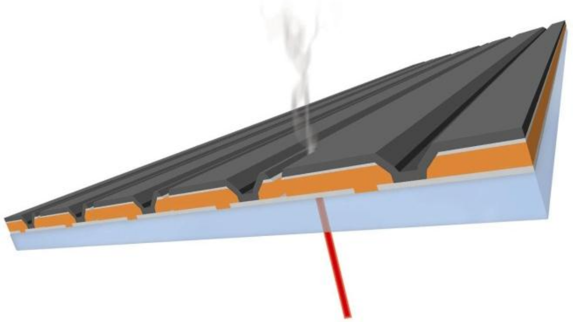


Design of LMA fibers

Advanced Lasers for Photovoltaic INdustrial processing Enhancement

- Scaling of the fiber Mode Field Area in single-mode fibers is ultimately limited by two factors:
  1. The accuracy of the index difference between core and cladding:

     the limit is NA > 0.06

     Core Diameter $\cong$ 13 **μ**m at λ = 1 **μ**m
  2. The fiber bend loss which increases rapidly with increasing A_{eff}.

     Proper launching conditions and bending can give $D_{core} \cong$ 30 **μ**m, but the price is the mode profile deformation.

- Refined design approaches with specially optimized refractive index profiles allow for mode areas up to the order of 1000 μm^2.

  (rised outer ring, moat, double ring, parabolic profile, chirally coupled, multi-core, leakage channel, …)

- **Photonic Crystsl Fiber technology provides a flexible solution**

Effective Mode Area

$$A_{eff} = \frac{\left[\int_S I(x,y)\,dxdy\right]^2}{\int_S I^2(x,y)\,dxdy}$$

where I is the field intensity distribution of the fundamental mode of the fiber over the all transverse section.

Effective Area

ITU-T Rec. G.650.2 (06/2002)

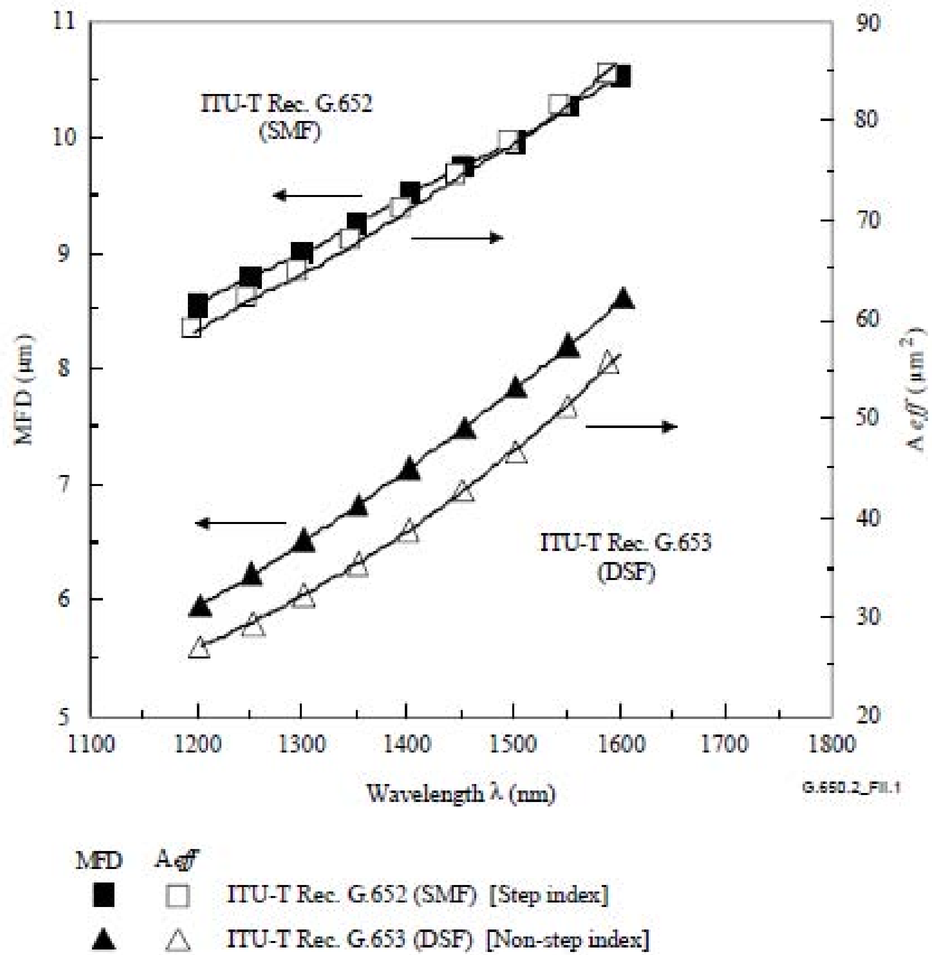
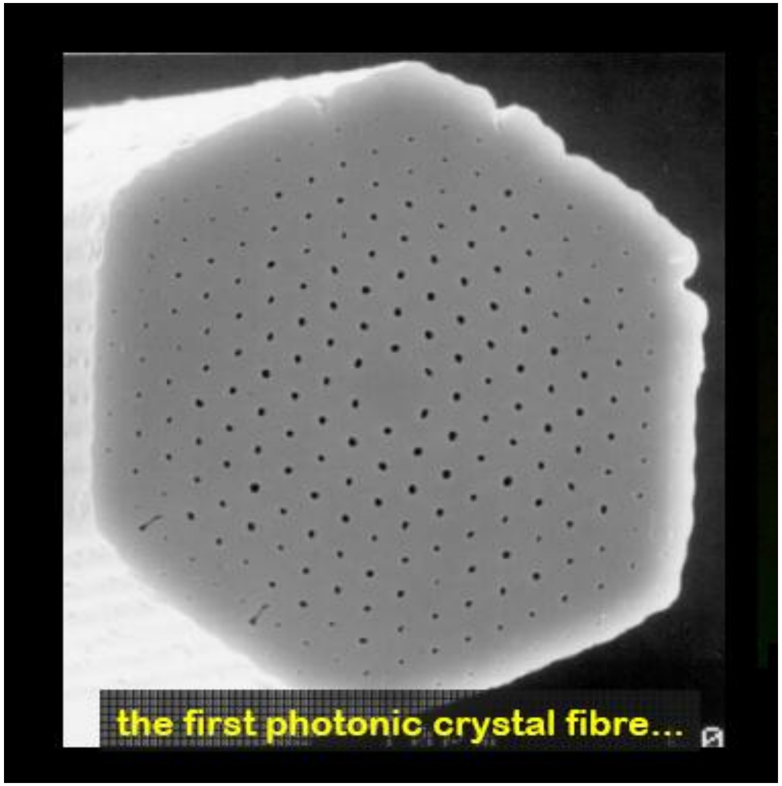
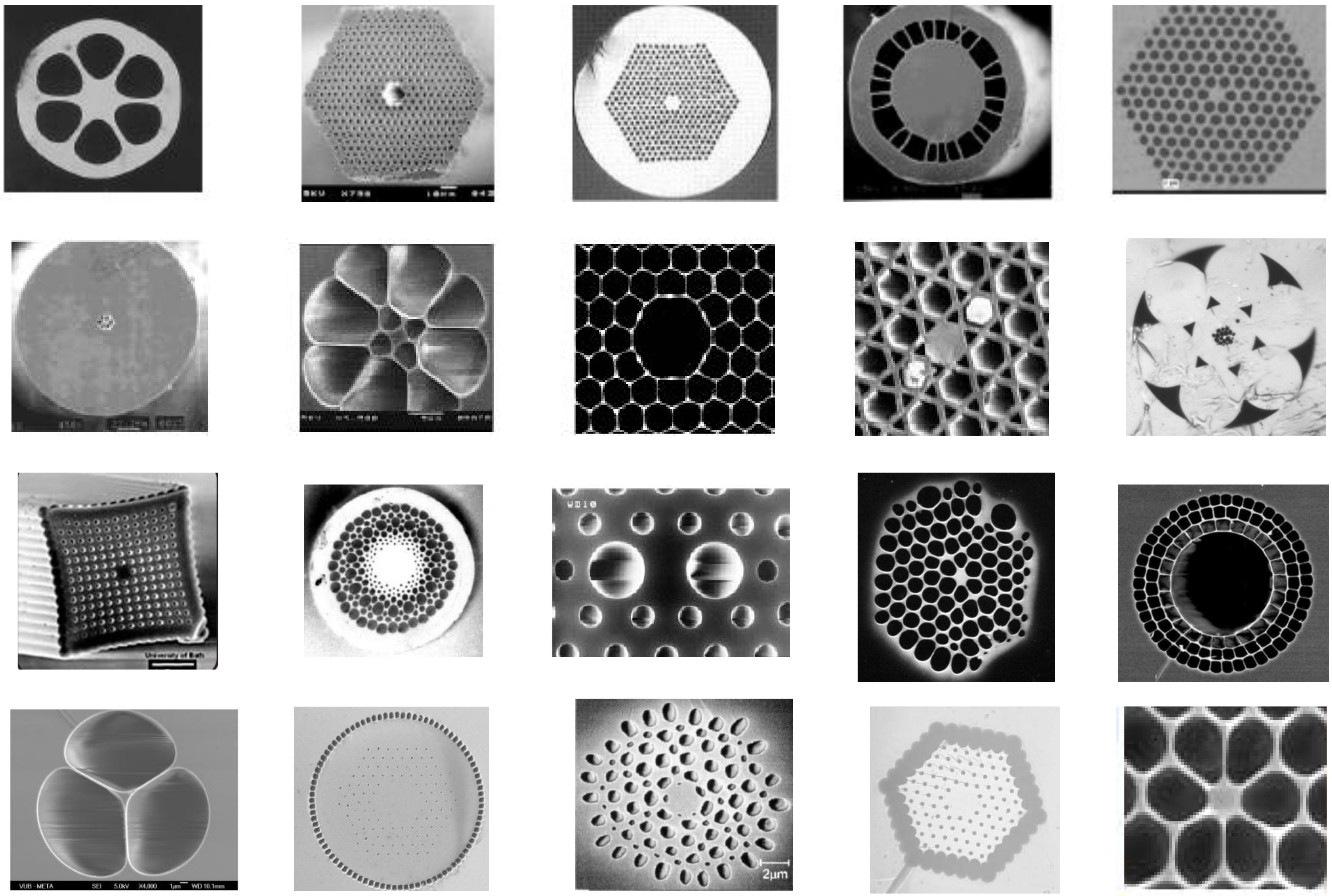


Figure II.1/G.650.2 – Example of measured wavelength dependence of A_{eff} and MFD (= 2W) of G.652 and G.653 fibres

Photonic Crystal Fibers

- Philip Russel in 1991
- Particular air hole distributions
- Solid core
- Hollow core
- Newer guiding properties
- Compatibility with standard technologies (doping, gratings, …)

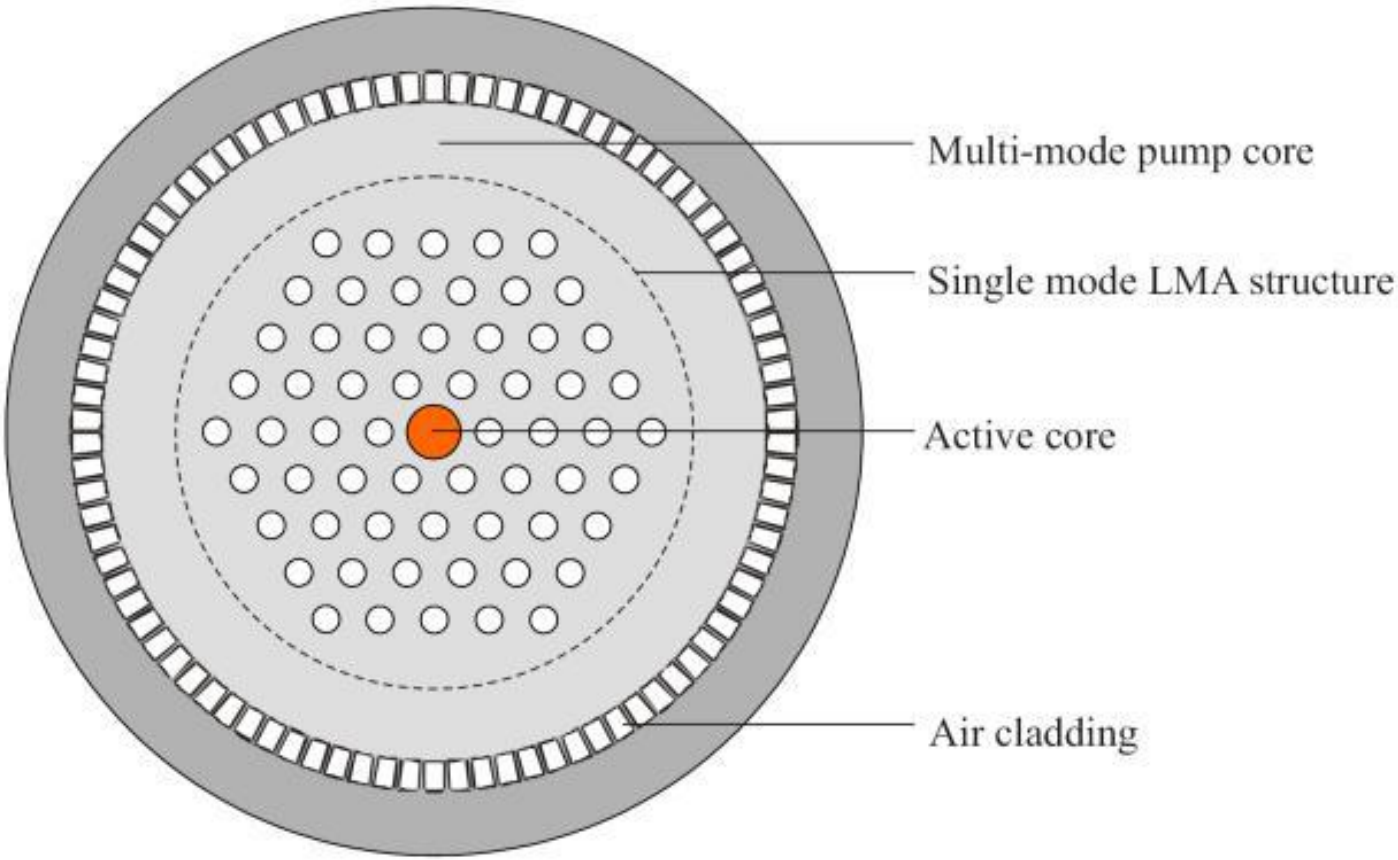



2μm

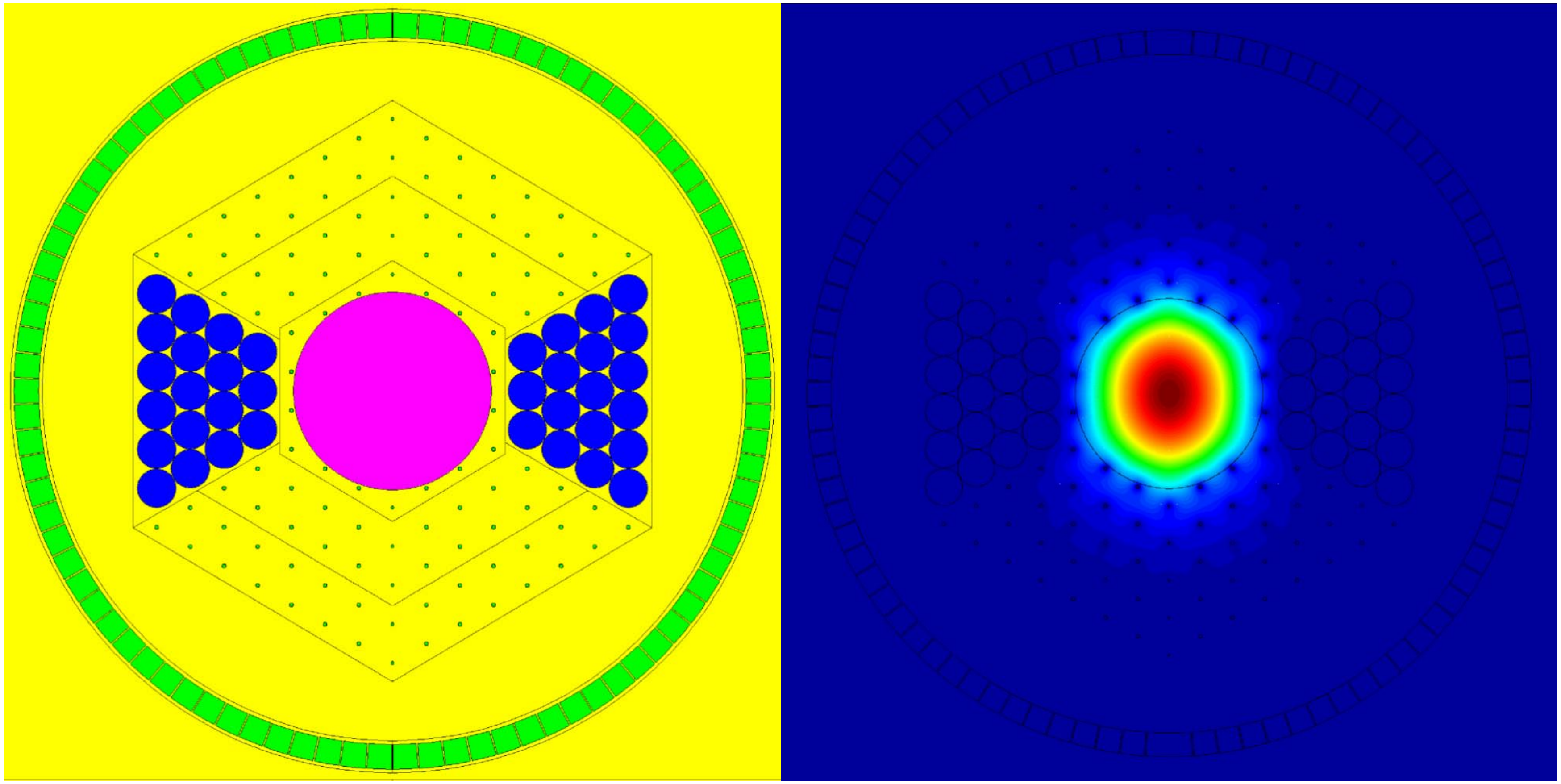
Flexible and rod fibers

- **Double clad** fibers made with photonic crystal fiber technology.
- Extremely **high NA for the pump** core/inner cladding, allowing efficient pumping with inexpensive / high power pumps.
- High power levels avoiding nonlinearities and providing a **good overlap** between the pump guide and the signal guide area.
- The all glass design has a much **higher damage threshold** than standard double-clad fibers.

Yb-doped PCF


Multi-mode pump core
Single mode LMA structure
Active core
Air cladding

PM fiber



Polarizing fiber

Advanced Lasers for Photovoltaic INdustrial processing Enhancement

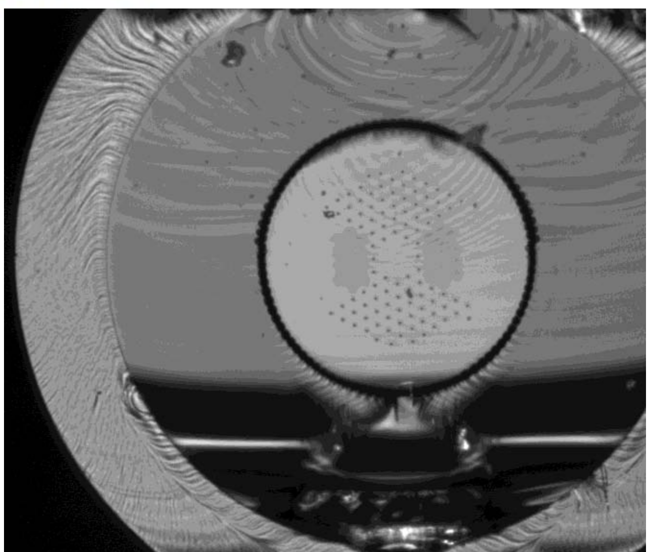
DC-200-40-PZ-Yb-01

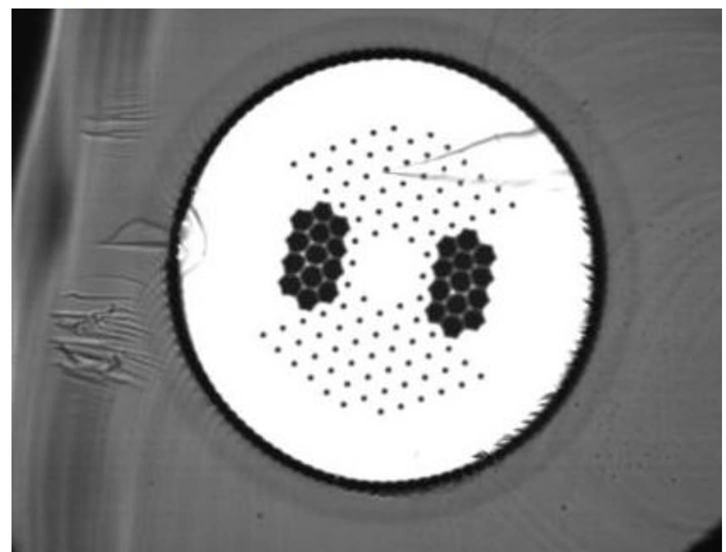
Polarization Maintaining · Rare Earth Doped · Large Mode-area · Single Mode

Single-mode, polarizing double-clad Ytterbium-fiber with large mode area

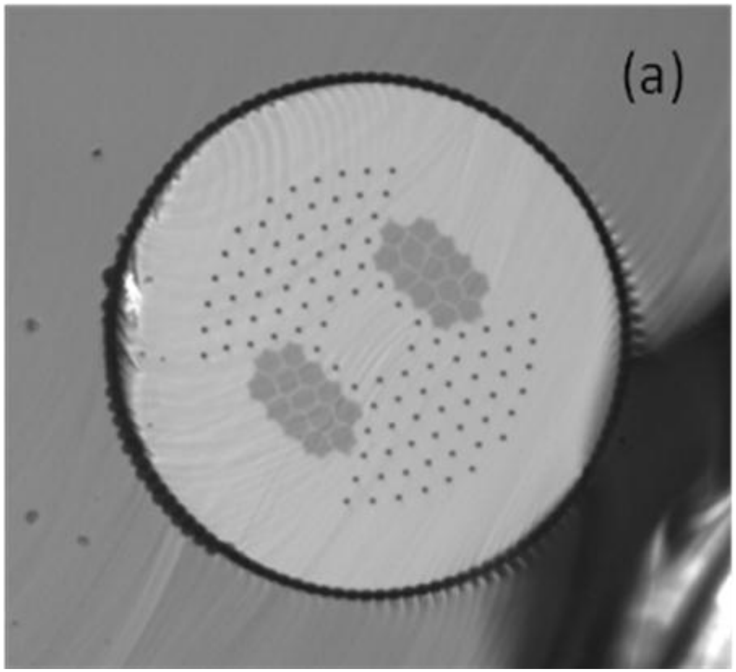
Optical properties	
Signal core	
Mode properties (1)	Single mode
M^2 @ 1060 nm (1)	< 1.3
Mode field diameter	29 ± 2 µm
Mode field area	650±100 μm^2
NA @ 1060 nm	~ 0.03

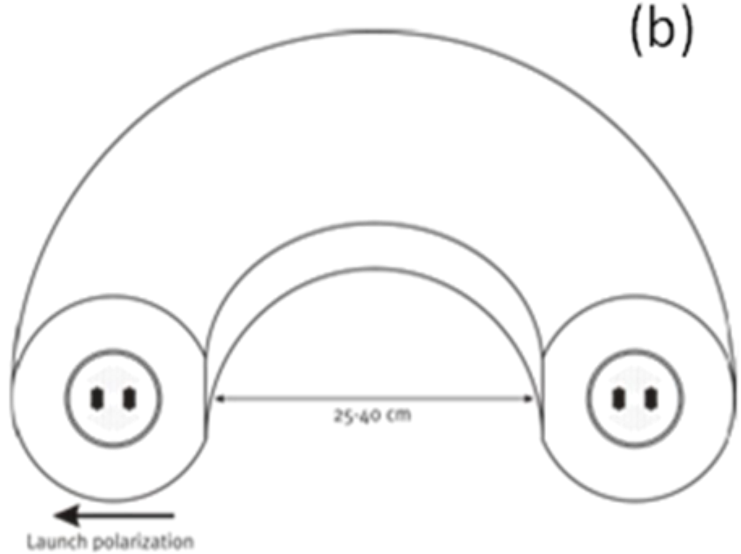
NKT Photonics
the power of light

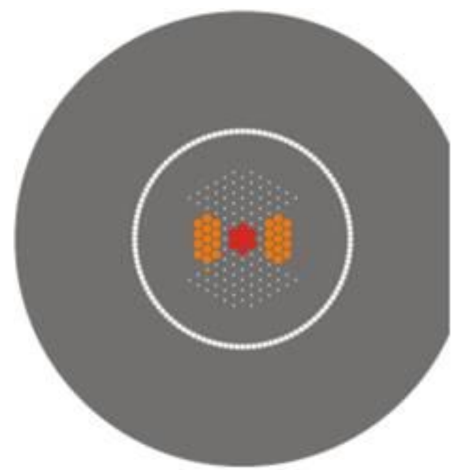




Yb-doped, DC, PM PCF

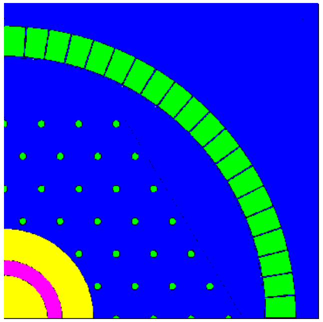


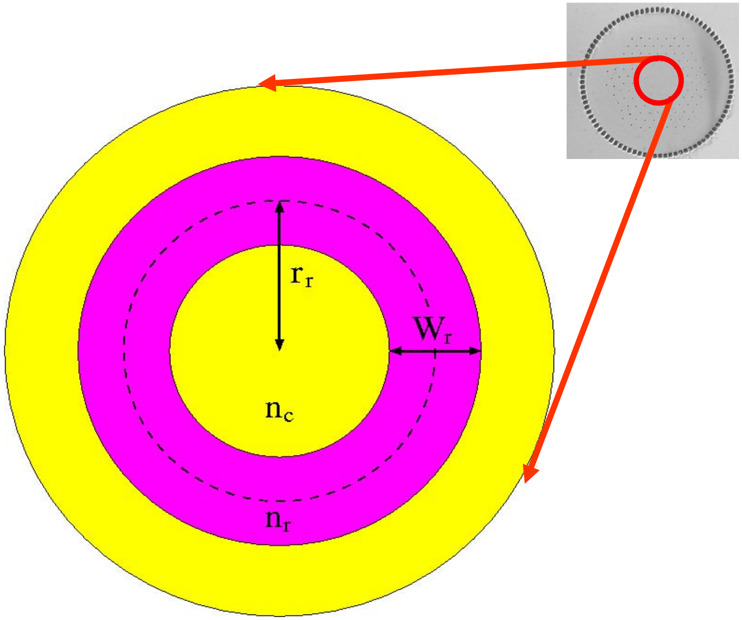




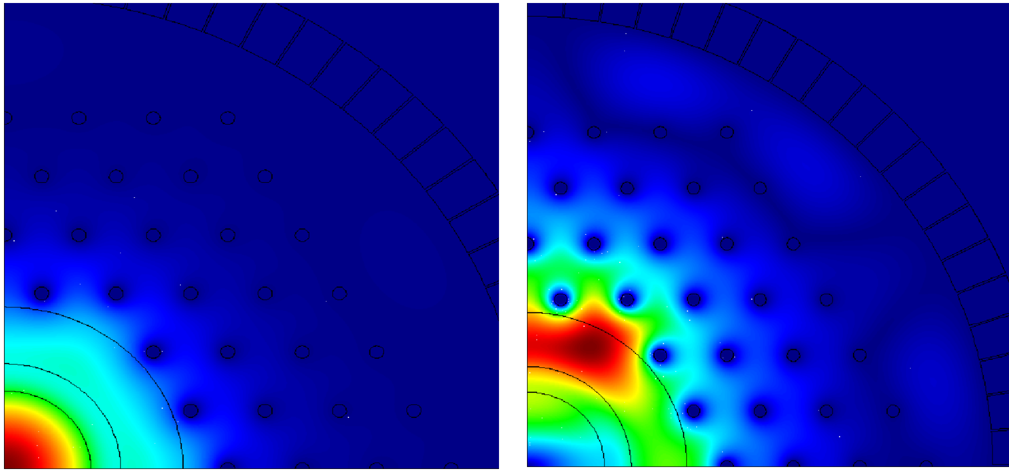
Picture of the fabricated PCF and diagram of the asymmetric fiber design, which enables coil control. By **NKT Photonics**.

Rod: sectioned core

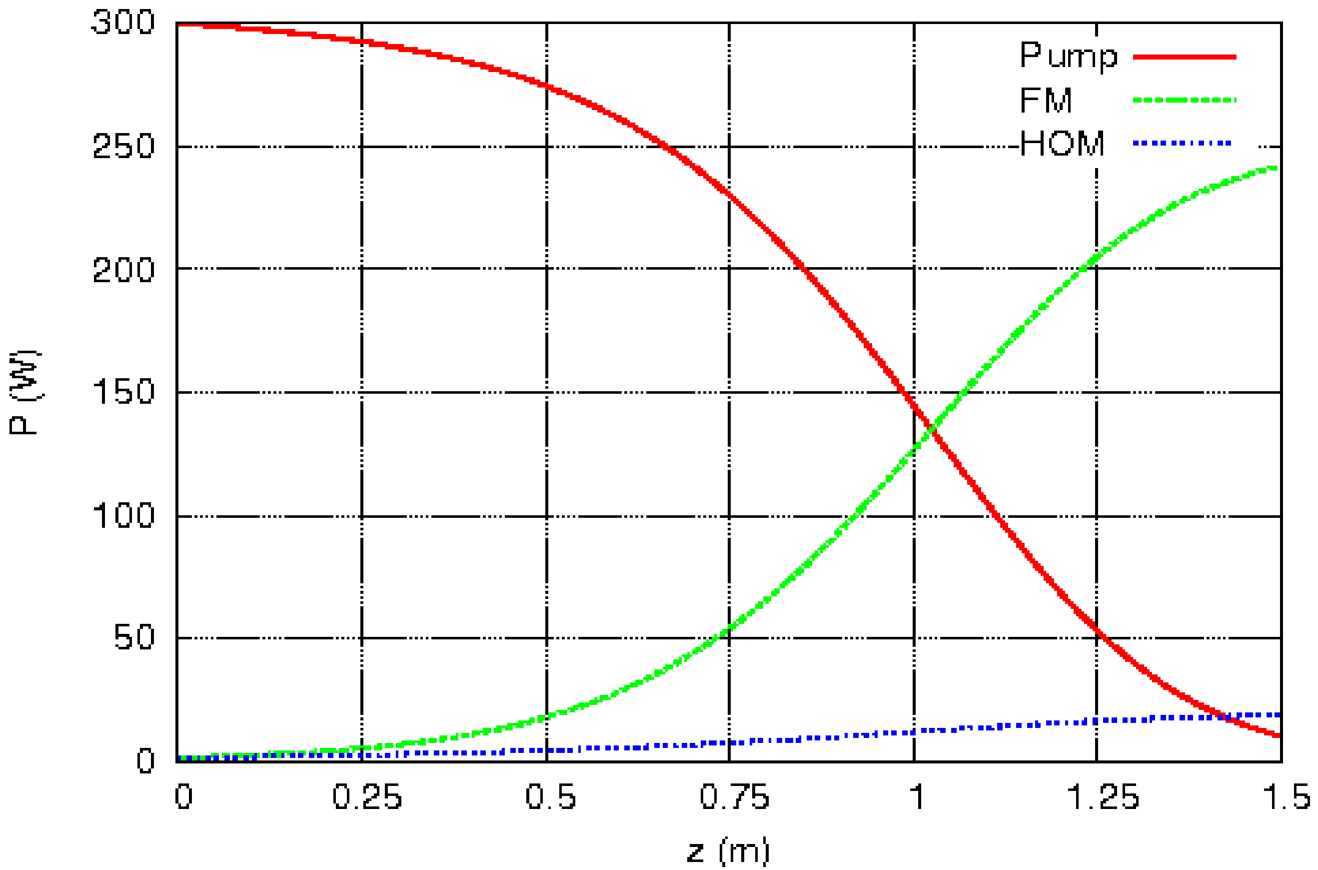




- Fundamental mode and higher order modes with different spatial distribution.
- To reduce the refractive index where HOM are more confined.
- To design a core with rings having different refractive index.

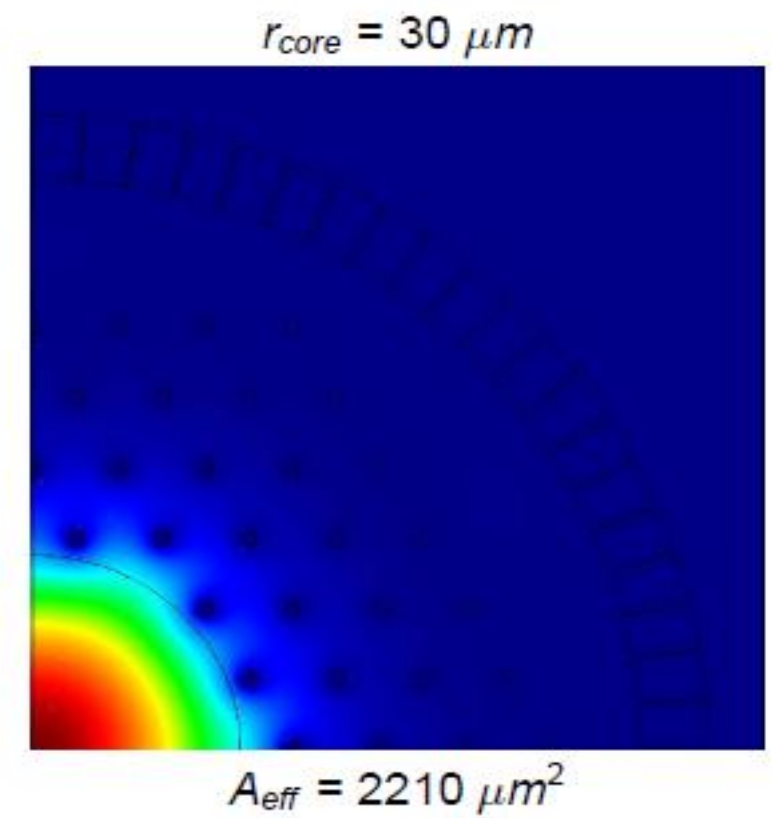


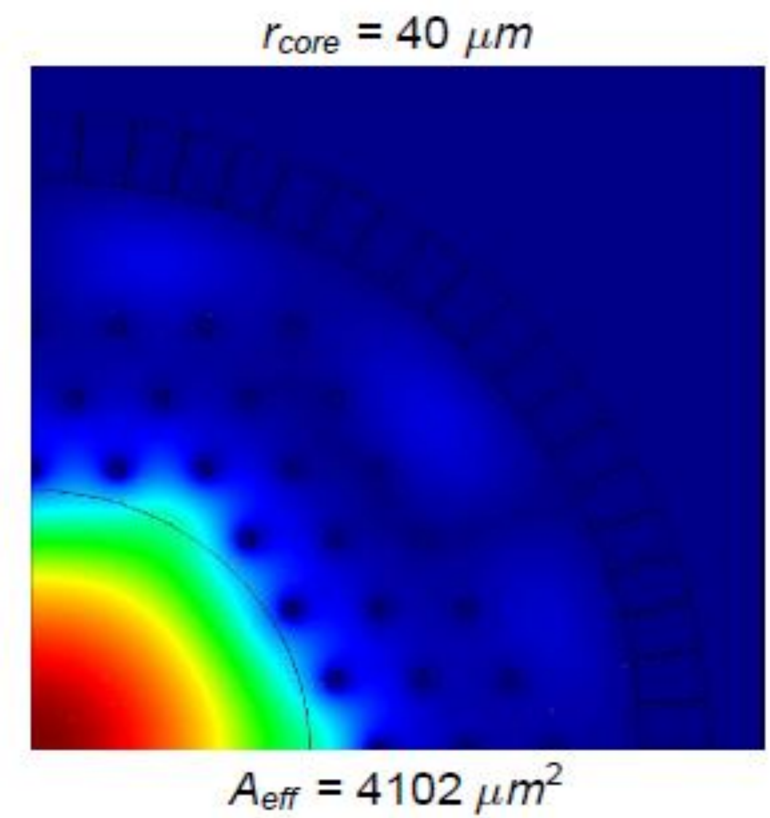
Differential gain



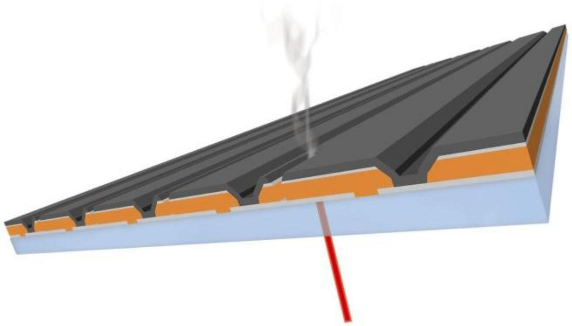
The differential gain assures the fiber to be effectively single mode.

Rod: effective area





Summary



- Scribing of photovoltaics modules
- MOPA and Q-switched fiber laser
- Narrowband seed laser
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- PV module production and evaluation
- Conclusions

PV module production

Five partners involved in PV module production:

1. Solar System & Equipment provides samples of both CdTe and CIS to the laser partners. **Sputtering** to obtain $CuInGaSe_2$/CdS solar cell. On flexible substrates and on **commercial ceramic tiles** (PvT) (for buildings integration).

2. NEXCIS produces CIS solar cells from **electrodeposition**. NEXCIS will provide electrodeposited CIS both **on glass and on flexible substrates.**

3. ZSW - Zentrum für Sonnenenergie- und Wasserstoff-Forschung (Centre for Solar Energy and Hydrogen Research) is equipped for the small scale fabrication and analysis of **CIS thin film** solar modules up to a size of 30 cm x 30 cm. Certified best cell efficiency of 20.4% realized in 2010 (area of 0.5 cm^2).

4. Würth Solar GmbH & Co is equipped for thin film solar module technology based on **$Cu(In,Ga)Se_2$ mass production**. It has a production line at a capacity of 30 MWp/y.

5. University of Verona carries on research activity on **CdTe** solar cells, in particular application of innovative **polymer substrates**, back contacts and new configurations

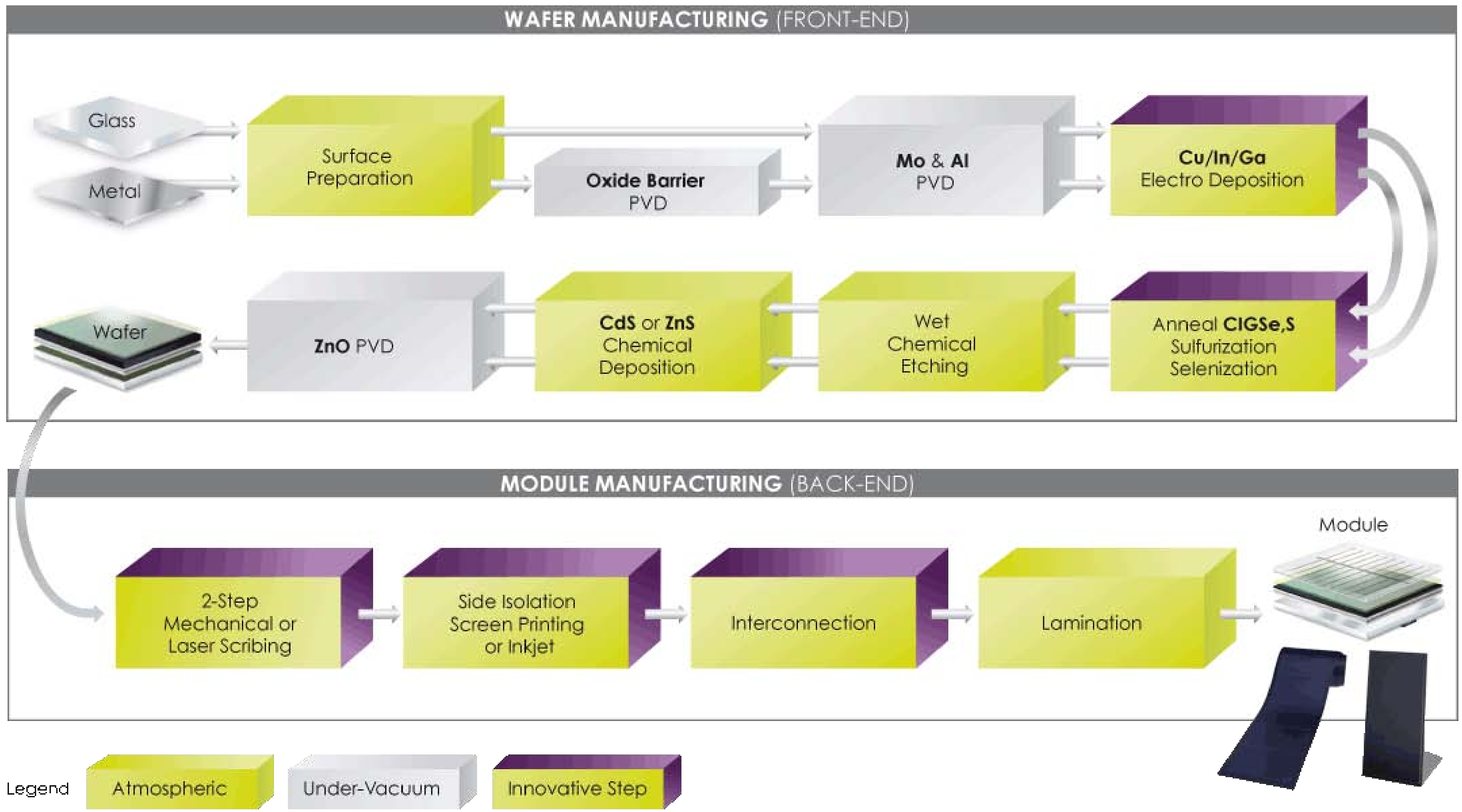
PV module evaluation

Analytical methods to evaluate the scribing operations:

1.optical microscopy,
2.scanning electron microscopy,
3.electrical insulation test,
4.I-V characterization,
5.thermal imaging.

Activity by Joint Research Center, European Commission – Institute of Energy, Renewable Energy Unit

Module manufacturing

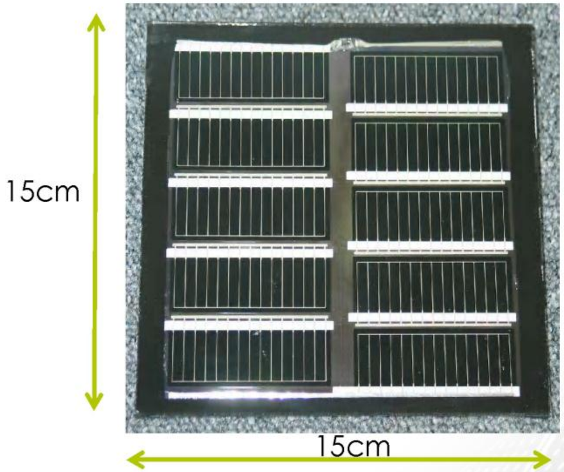


Module manufacturing process by electrodeposition at **Nexcis**

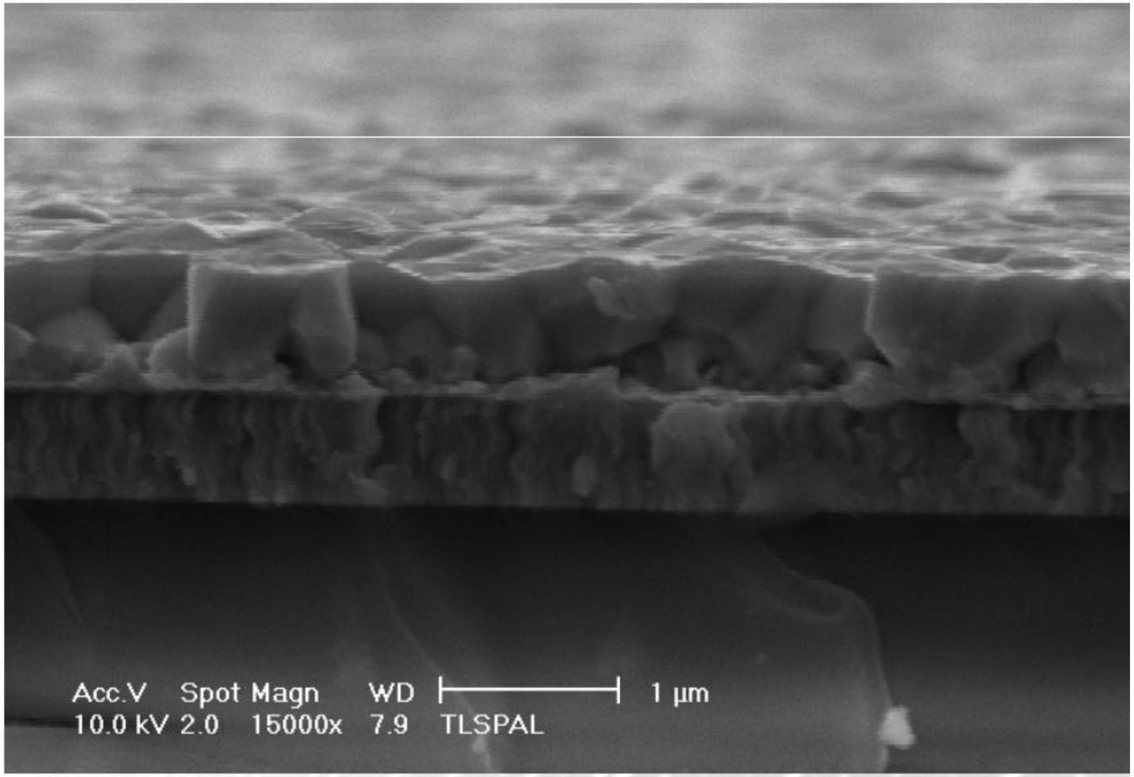
Homogeneity

Homogeneity is a key point for a successful product:

- Good compacity
- Good adhesion
- Low roughness



- Efficiency certified by ISPRA: 8,6%
- Efficiency measured at Nexcis: 8,5%



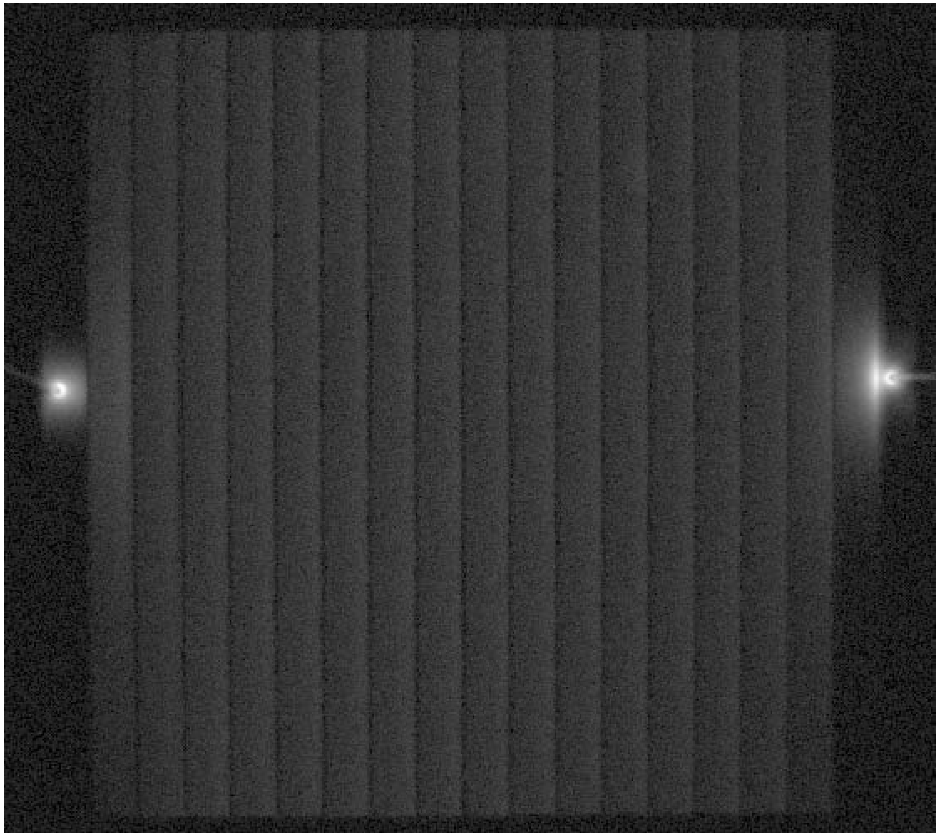
First certification of Nexcis module (CIS2) on glass

P1 scribe image, Mo on glass

The P1 groove shown is of poor quality mainly due to the high pulse duration of 100 ns.
The edges of the back contact consist of jagged pieces which are broken off the layer.
Also, faint cracks draw through the glass surface and the edges of the back contact.

P1 groove of high quality

Thermography test



Thermography test used **to find out shunts and series resistances** by applying, to the samples in the dark, **forward bias** current somewhat below the short circuit current. No localized shunts are detectable. No pronounced thermal signal from the ZnO-Mo interconnect is visible which would indicate an increased contact resistance in $P_{2.}$

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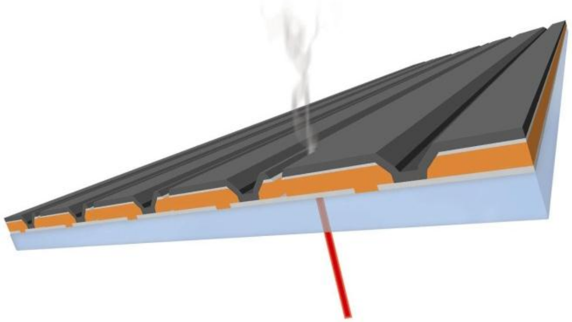

Conclusion

Very interesting application of fiber lasers.

Future steps:

- Fully fibered MOPA design and fabrication.

- Final PCF design for the laser booster stage.

- High power seed diodes.

- Glass substrate modules with more than 1X% conversion efficiency at less than 1 €/Wp production cost.

- Production of metal/polymer modules:

  advantage of low-cost, reduced weight by a factor of 10 compared with the classical glass substrate.

  Also on ceramic tiles.

Grazie!