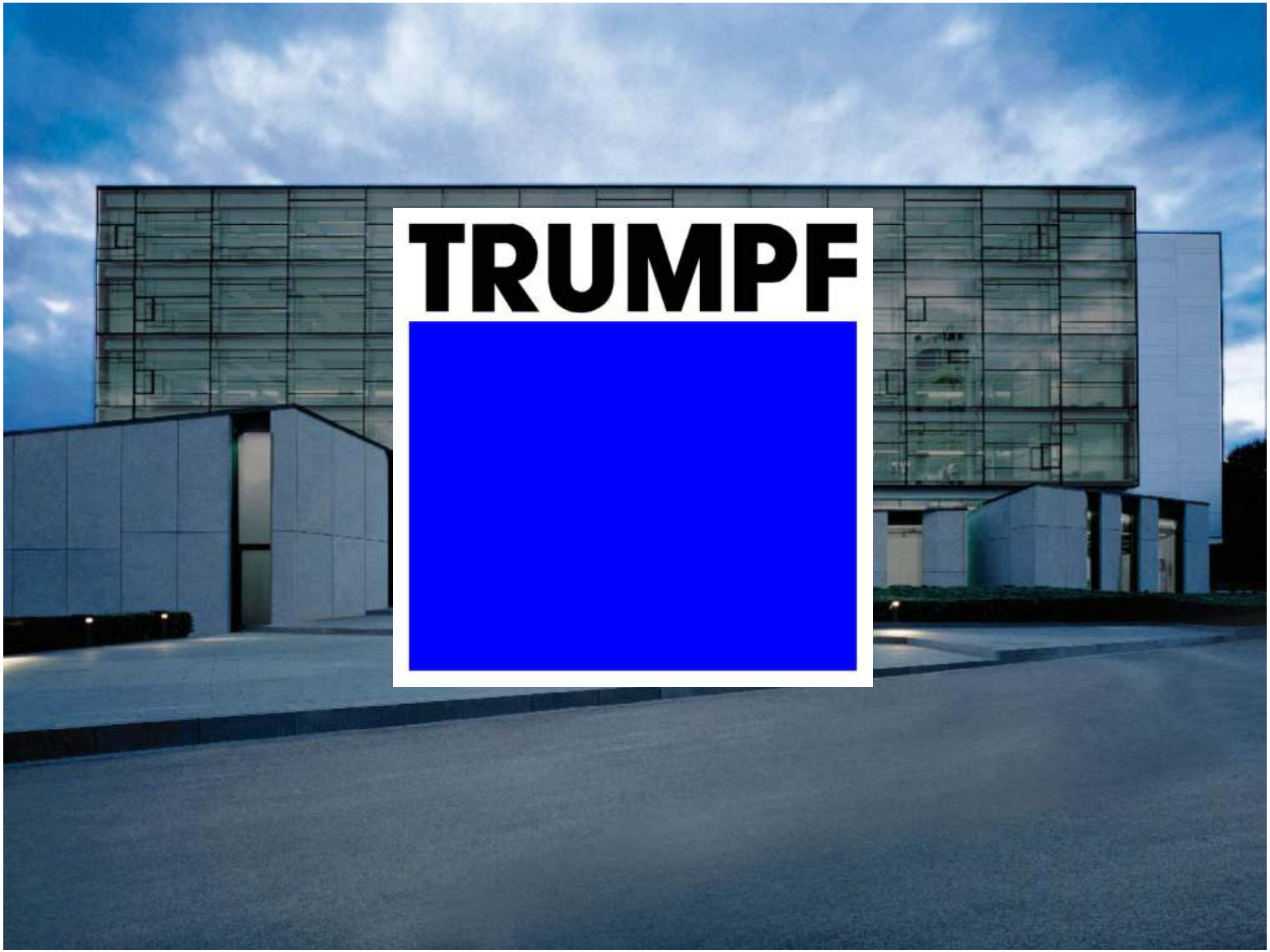
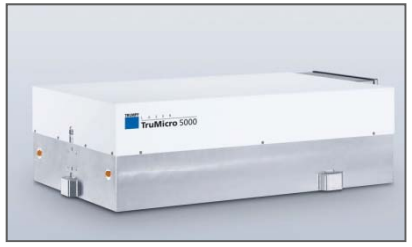
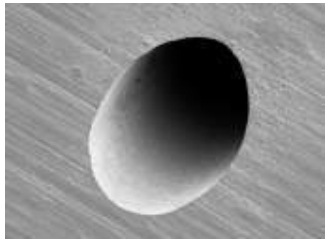

TRUMPF

Disk based amplification ps lasers and their applications





TRUMPF (China) Co.,Ltd.
蔡伟军
Manager Low power laser division
13913591512
William.Cai@cn.trumpf.com

About Trumpf

We are a high-tech company that focuses on manufacturing technology, laser technology and medical technology.

We offer our customers both innovative and high-quality products.

We are represented in all world markets,
close to our customers with 58 subsidiaries.

We are a family business established in 1923 and our goal is to stay economically independent.

Our Products and Customers

Machine Tools/ Power Tools

Machine Tools


Metalworking industry (mechanical / apparatus engineering, vehicle construction, electronics /switching cabinets)

Laser Technology/ Electronics

Laser Technology

Automotive and suppliers, electronics /precision engineering, mechanical engineering, tool and mold making

Electronics

Plant engineering of systems for the production of semiconductors, flat screens, solar cells, coating of architectural glass

Medical Technology

Medical Technology

Hospitals and clinics

Contents

- Why shorter than short?
- How to obtain ideal pulses - TruMicro 5000
- Applications

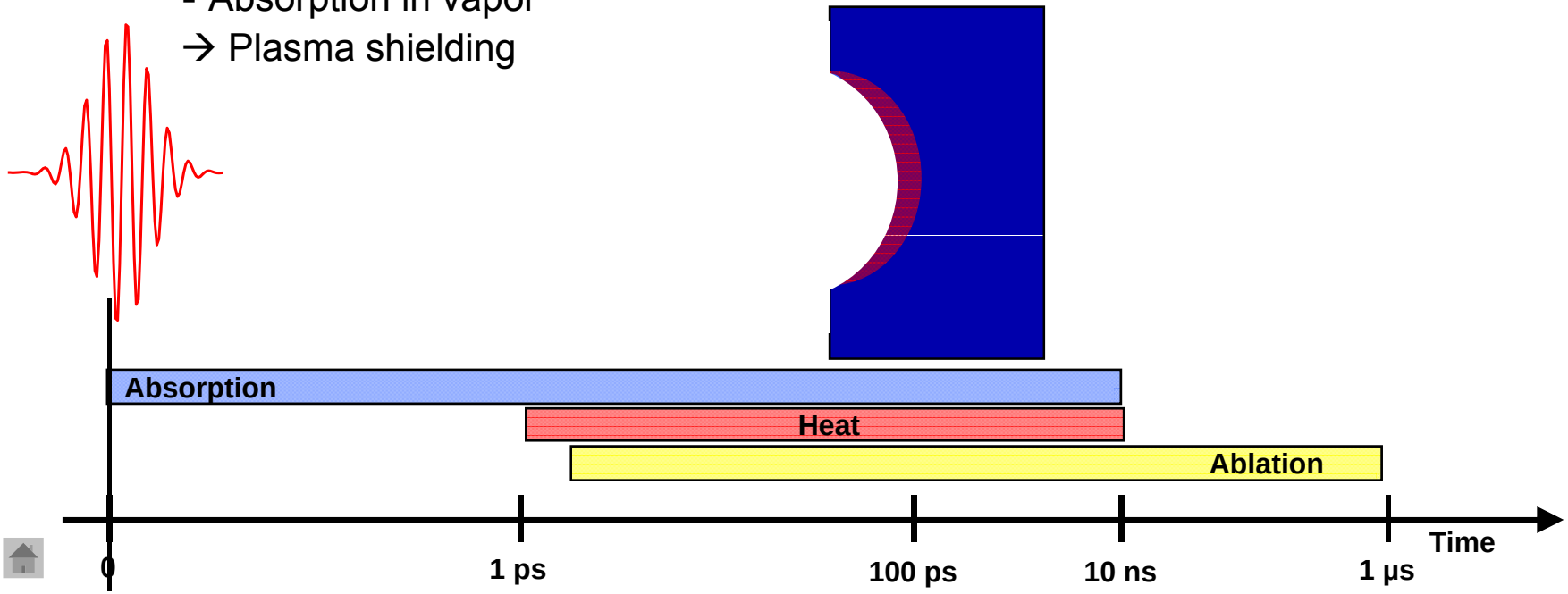
Contents

- **Why shorter than short?**
- How to obtain ideal pulses - TruMicro 5000
- Applications

Nanosecond Pulse Laser - Material Interaction

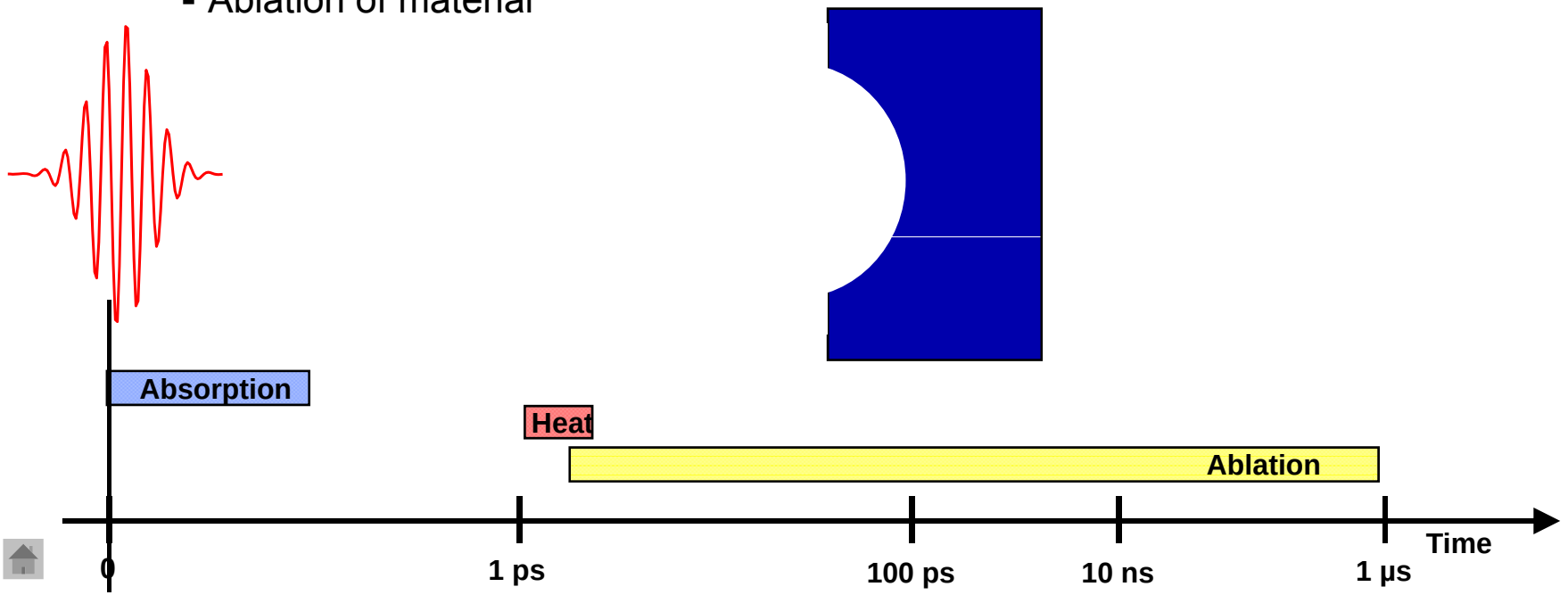
- Absorption exceeds Electron-Phonon-Interaction-Time (EPIT)
- Thermal equilibrium between electrons and lattice
- Melt phase + vapor phase (ablation)
- Absorption in vapor

→ Plasma shielding



Ultrashort Pulse Laser - Material Interaction

- Energy transfer from (pulsed) laser light to electrons (absorption)
- After Electron-Phonon-Interaction-Time (EPIT)
- Energy transfer from electrons to phonons: Heat
- Ablation of material



TRUMPF

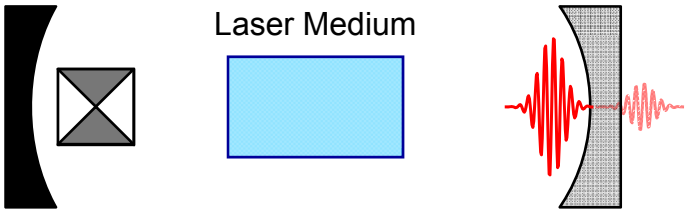
Contents

- Why shorter than short?
- **How to obtain ideal pulses - TruMicro 5000**
- Applications

Obtaining ps-Pulses

ps (and fs) Oscillators:

- Tens of MHz repetition rate (given by resonator length)

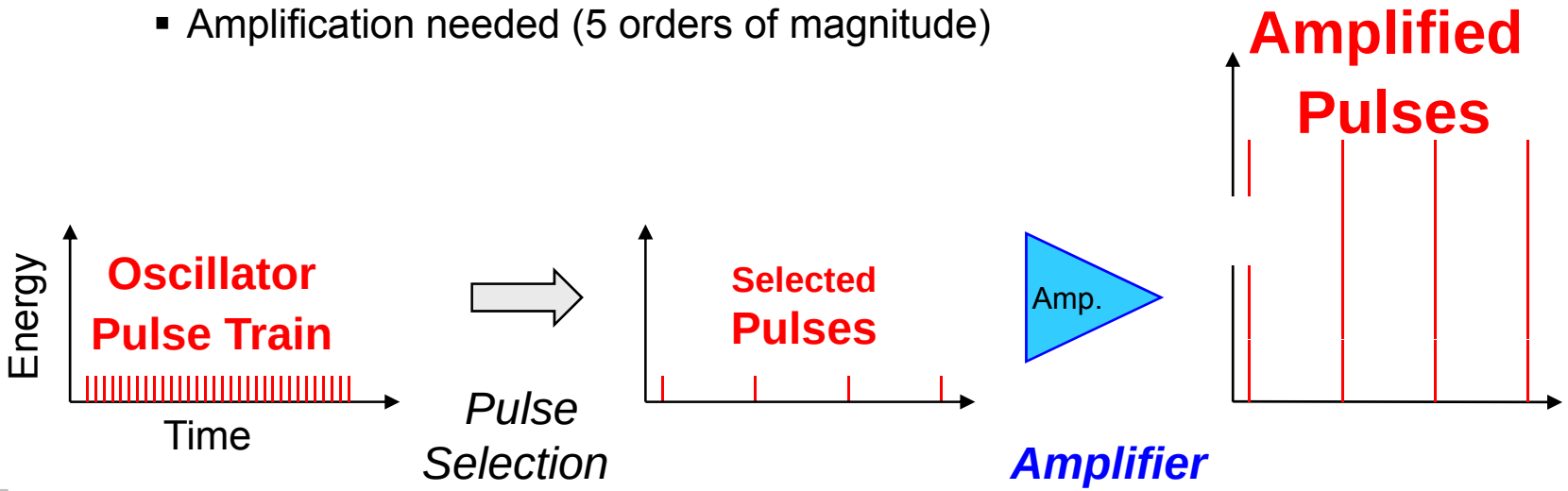


Obtaining ps-Pulses

ps (and fs) oscillators:

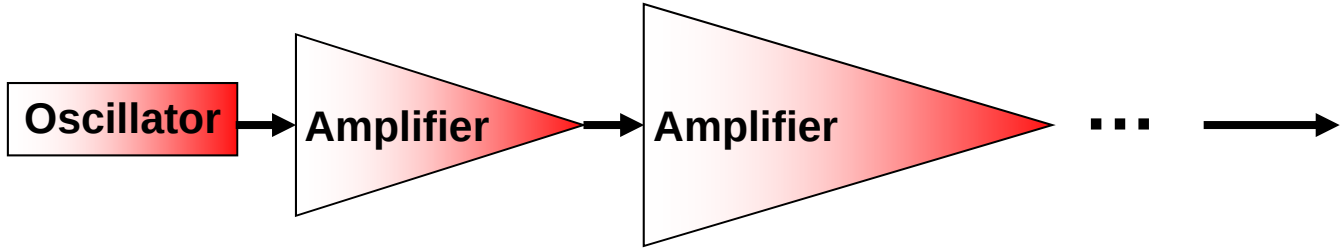
- Tens of MHz repetition rate (given by resonator length)
- Pulse selection to lower repetition rate

- Pulse energies in nJ scale
- Amplification needed (5 orders of magnitude)



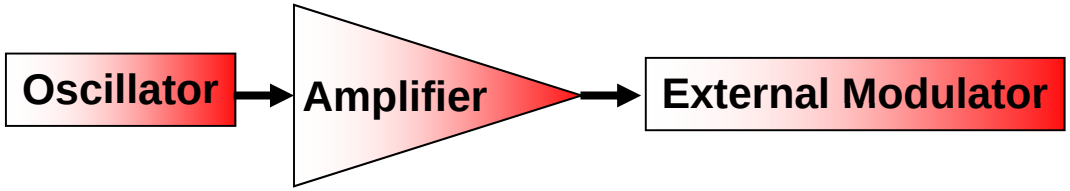
Comparison of Concepts for Amplification

- Linear Amplifier (e.g. rod, fiber, slab)



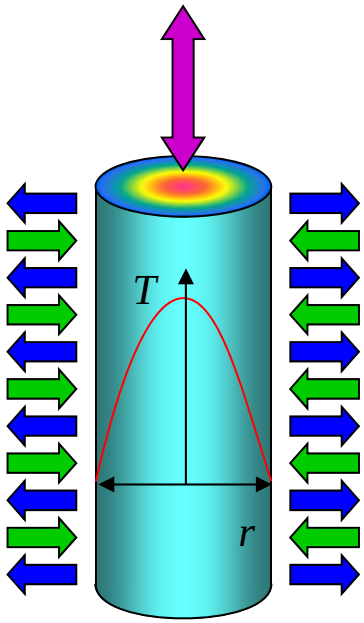
☹ First pulse issues; rod laser: beam distortions accumulate

- Regenerative amplifier (e.g. disk)



☺ No first pulse issues, TEM00 resonator guarantees beam quality

Solid State Laser Concepts

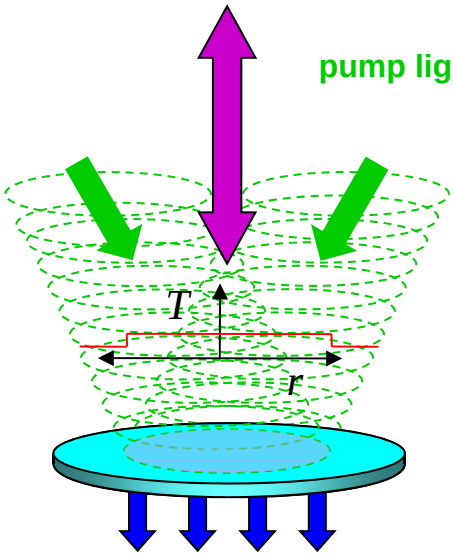


Parabolic temperature profile

Cooling and pumping
through lateral surface

Rod laser

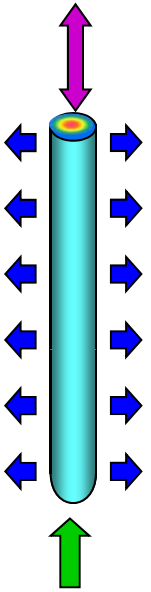
Laser emission



Flat temperature profile

Cooling through
ground surface

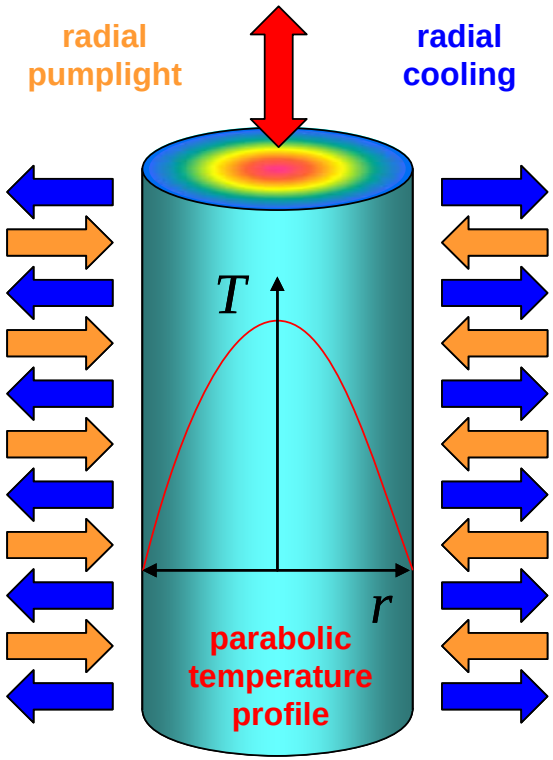
Disk laser



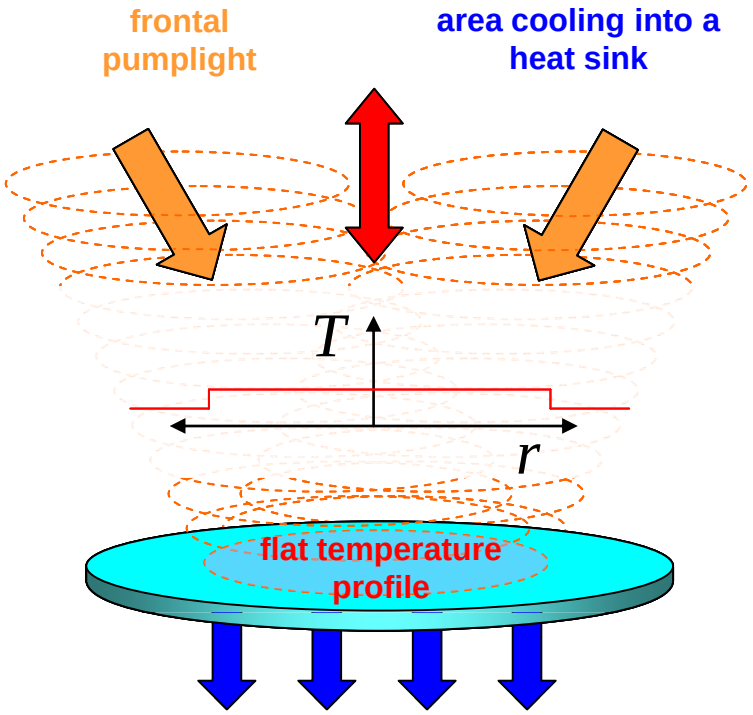
Cooling through
lateral surface

Fiber laser

Cooling Mechanism: From Rod to Disk



Rod laser

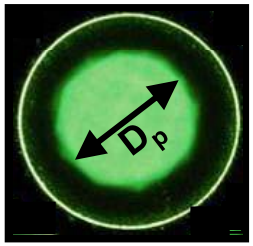


Disk laser

Scaling the Average Power of ps Lasers

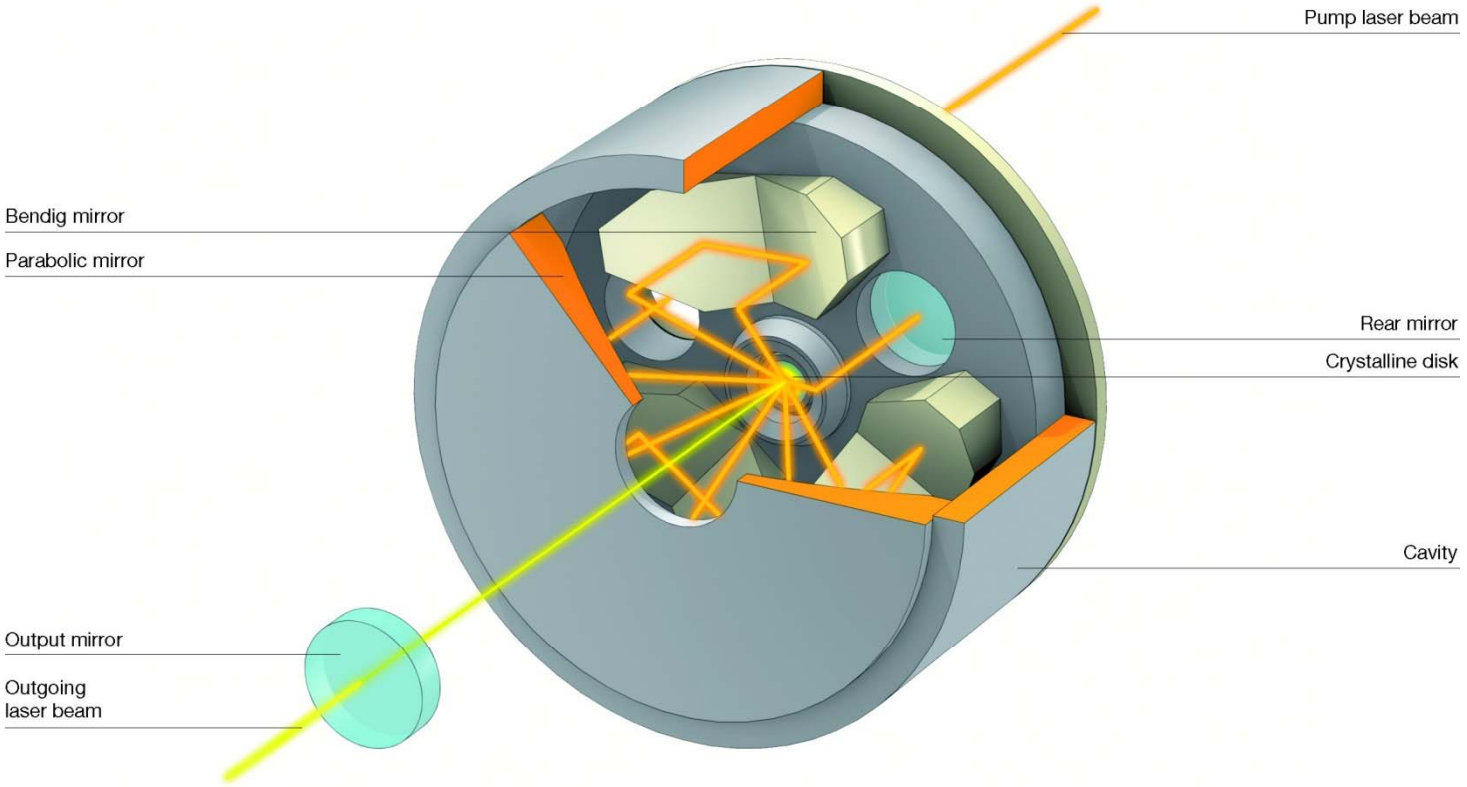
- Rod-type amplifiers:
  - Limited in average power due to thermal effects

- Most promising technology: Disk
  - Trumpf demonstrated a picosecond regenerative amplifier exceeding >100W (based on TruMicro 5000) already back in 2009

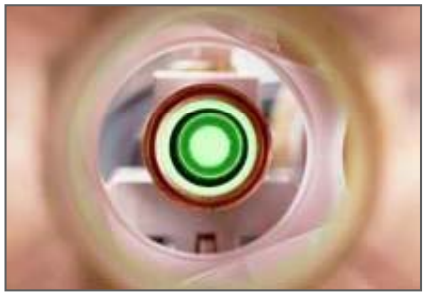


- Advantages:
  - High surface to volume ratio
  - Superior heat management
  - High average powers with good beam quality
  - No nonlinear effects / low intensities

DISK Laser

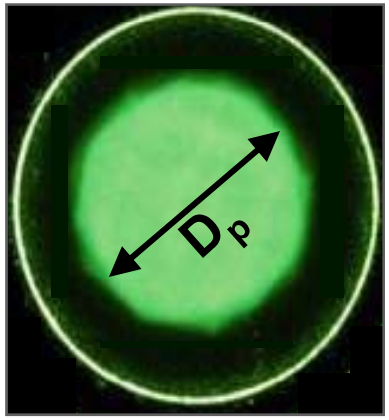

Pump laser beam
Bendig mirror
Parabolic mirror
Rear mirror
Crystalline disk
Cavity
Output mirror
Outgoing
laser beam

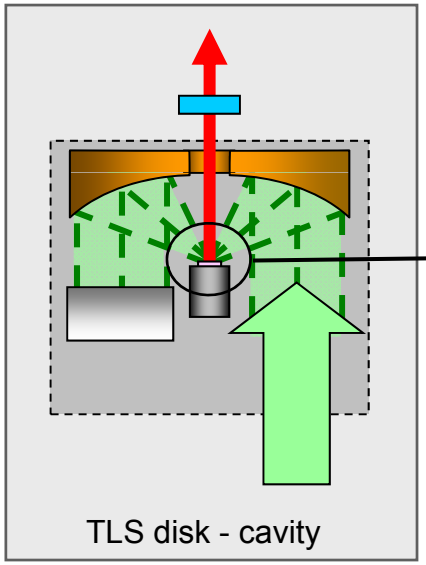
Scalability of Laser Output Power



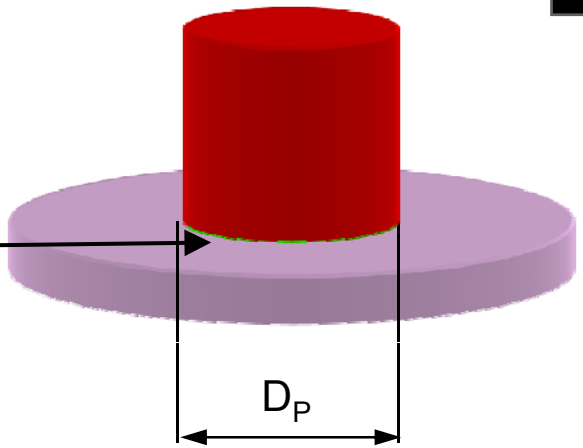
a certain laser power can be extracted per unit of area

$\Rightarrow P_L \sim D_p^2$



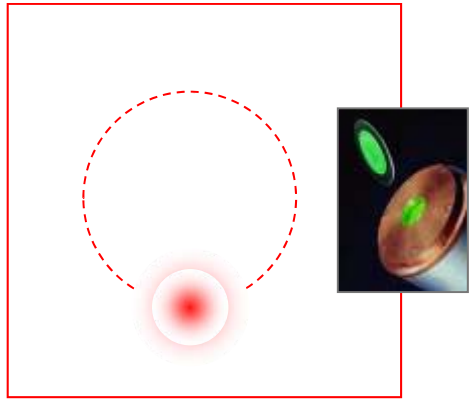


TLS disk - cavity



Pumped spot

TruMicro 5000 – Regenerative Thin Disk Amplifier



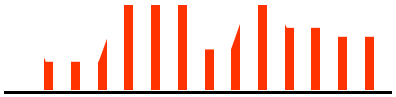
Thin Disk
Gain Medium

Oscillator

Seed Laser
generates picosecond pulses at low energy
(modelocked Fiber laser)

Thin Disk Amplifier
Ring Resonator

Highest Peak Powers
pulses million fold amplified to many tens of Megawatts

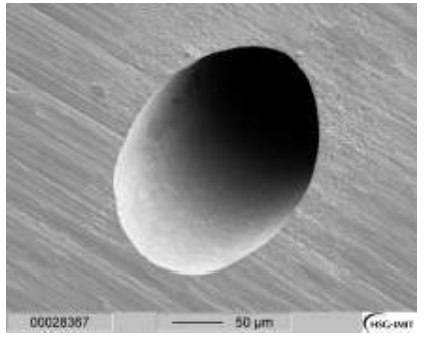


External Modulator
Pulse Selection & Modulation @ constant beam

TruMicro Series 5000 (compact)

100 cm x 60 cm

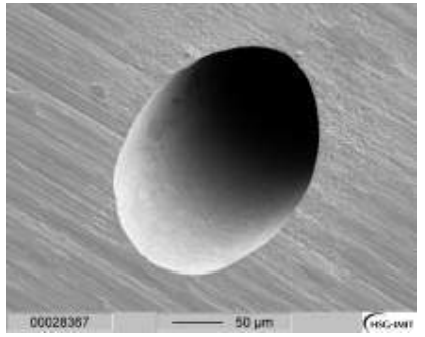
	TruMicro 5025	TruMicro 5225
Max. Average Power	25 W	15 W
Wavelength	1030 nm	515 nm
Pulse Duration	< 10 ps	< 10 ps
Max. Pulse Energy	125 µJ	75 µJ
Repetition Rate	200-800 kHz	200-800 kHz
Beam Quality	M ² < 1.3	M² < 1.3



TruMicro Series 5000 (compact)

100 cm x 60 cm

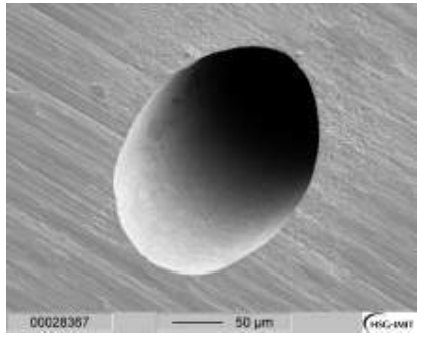
	TruMicro 5050	TruMicro 5250
Max. Average Power	50 W	30 W
Wavelength	1030 nm	515 nm
Pulse Duration	< 10 ps	< 10 ps
Max. Pulse Energy	250 µJ	150 µJ
Repetition Rate	200-800 kHz	200-800 kHz
Beam Quality	M ² < 1.3	M² < 1.3



TruMicro Series 5000 (compact)

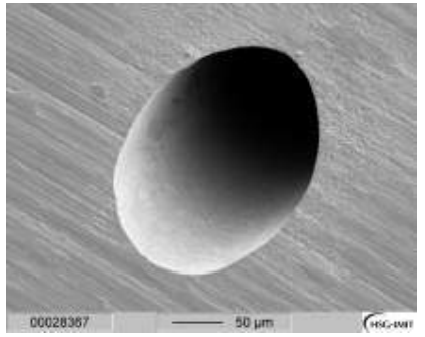
100 cm x 60 cm

	TruMicro 5070	TruMicro 5270
Max. Average Power	100 W	60 W
Wavelength	1030 nm	515 nm
Pulse Duration	< 10 ps	< 10 ps
Max. Pulse Energy	250 µJ	150 µJ
Repetition Rate	400-600 kHz	400-600 kHz
Beam Quality	M ² < 1.3	M² < 1.3



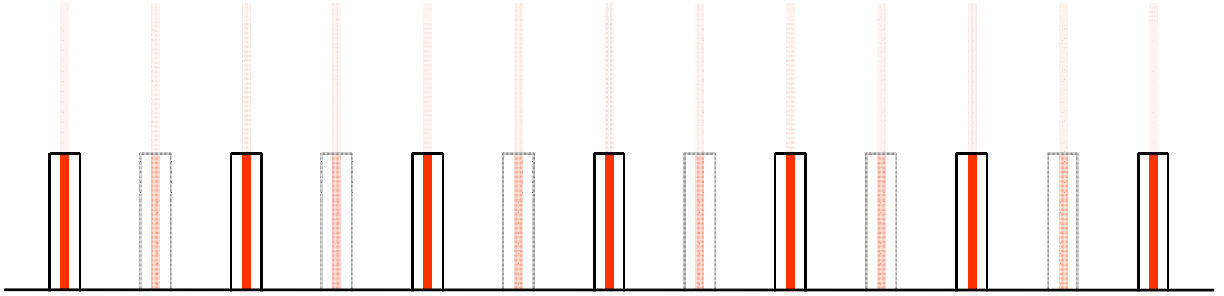
TruMicro 5350 / 5360

	TruMicro 5350	**TruMicro 5360**
Durchschnittsleistung	10 W	**15 W**
Wellenlänge	343 nm	**343 nm**
Pulsdauer	< 10 ps	**< 10 ps**
Max. Pulsenergie	50 µJ	**37.5 µJ**
Repetitionsrate	200-400 kHz	**400, 800 kHz**
Strahlqualität	$M^2 < 1.3$	**$M^2 < 1.3$**



- specified UV crystal life-time of more than 10 thousand hours of operation without using a micro mover

External Modulator



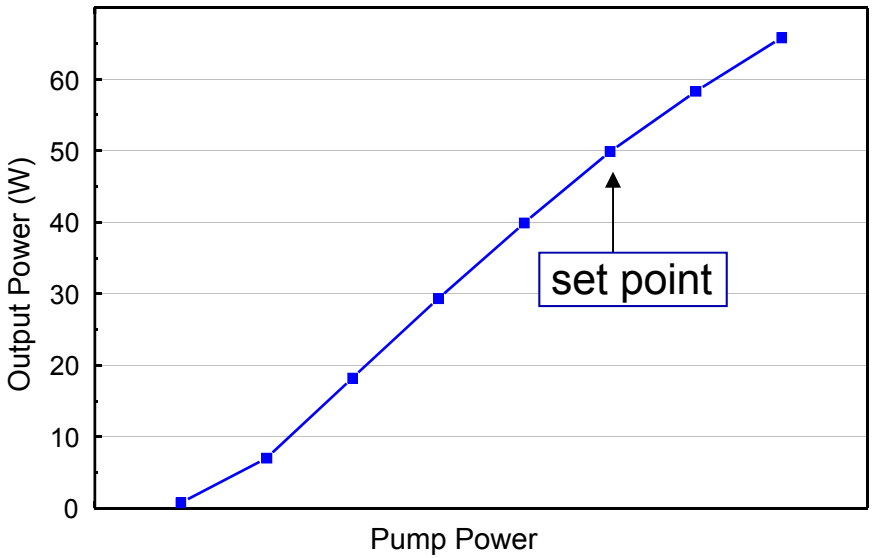
Features:

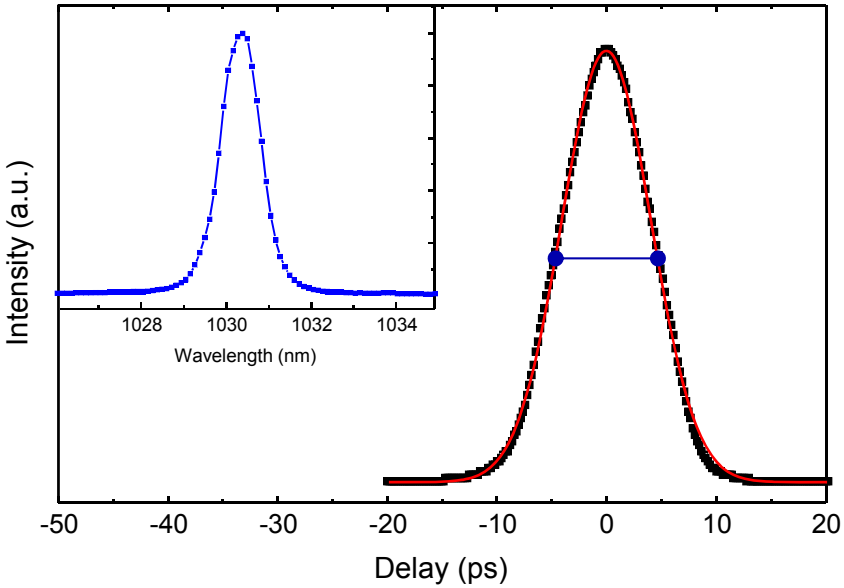
- Transmission given by HV (analog signal)
- Pulses triggerable, (e.g. every 2nd pulse)

Advantages:

- No first pulse issues!
- No variation of output beam properties (diameter, divergence) with power!

TruMicro 5050 – Power and Pulse Duration





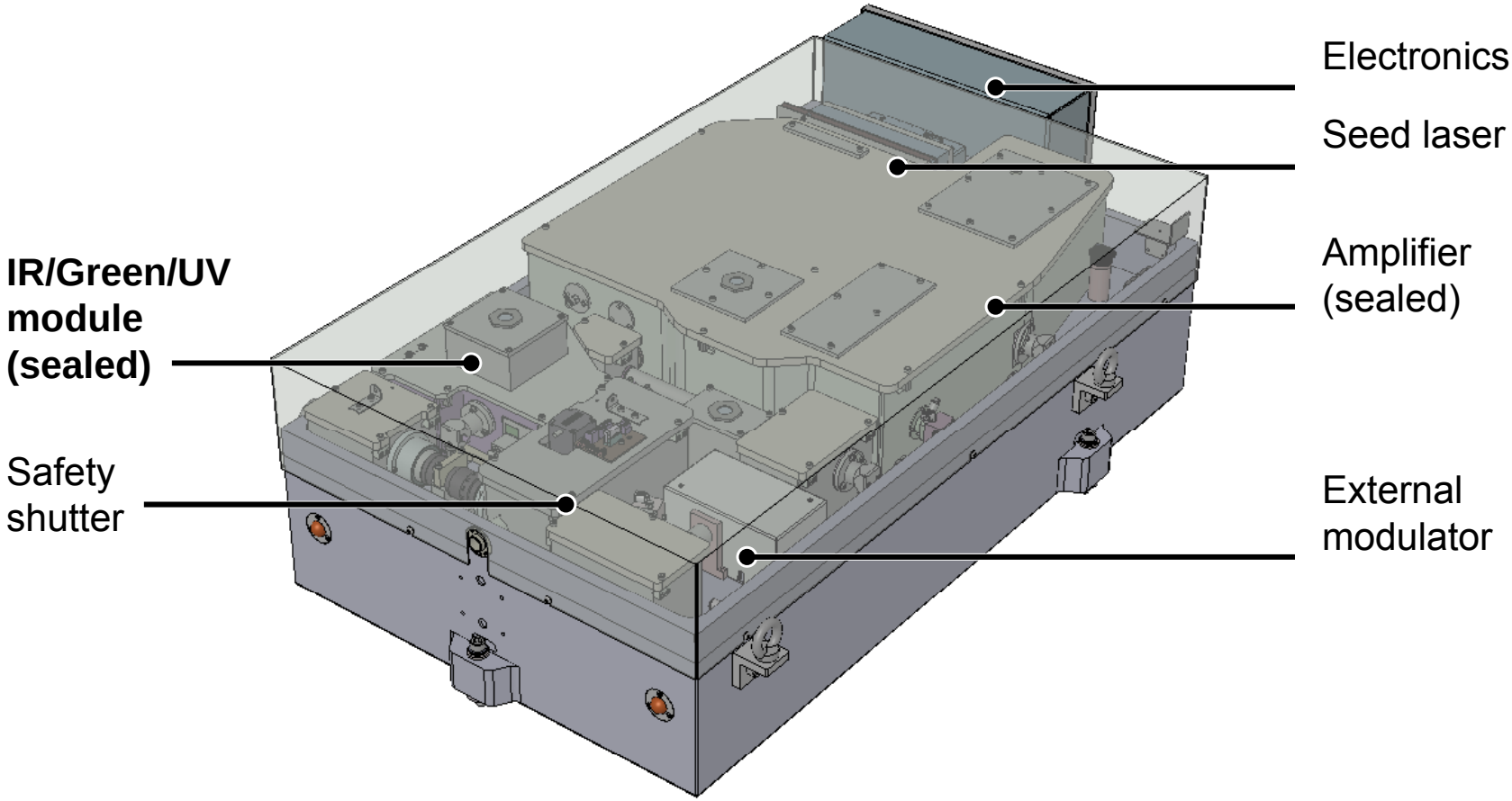
Average Power: > 50 W (max. 65 W)

Optical Efficiency: 50%

Pulse Duration: 6 ps ($sech^2$ Fit)

Spectral Width: 1 nm (FWHM)

Compact Laser Head – Main Components



TruMicro Series 5000 (compact)

TruMicro Ps Series Product roadmap

Lower average power Ps laser
≤10WTruMicro2000

Higher average power Ps laser 150WIR Ps

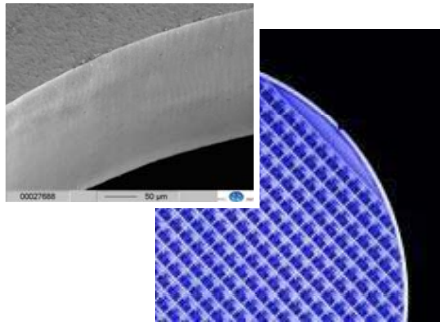
Shorter pulse duration＜1Ps

Contents

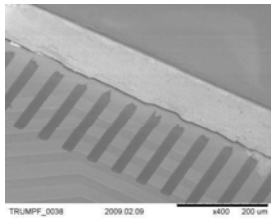
- Why shorter than short?
- How to obtain ideal pulses - TruMicro 5000
- **Applications**

Applications by Industries

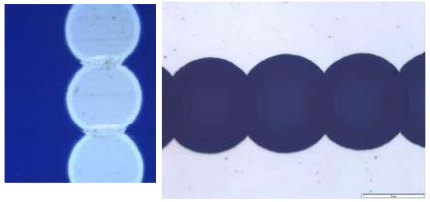
- Semicon
  - Cutting/drilling of Si-, Ge-, GaAs-, Sa-, AlO-, AlN- Wafers
  - Thin-film ablation (e.g. low-k)



- Flat Panel Displays
  - Cutting of thin glass

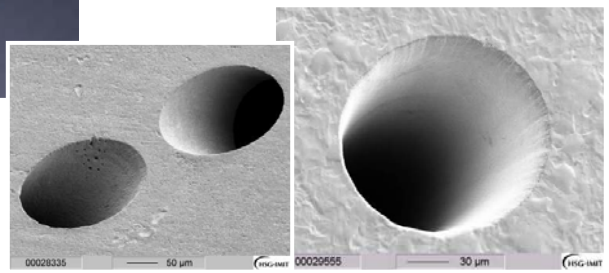


- Photovoltaics
  - Thin film ablation (e.g. P1-P3 scribing for CIGS solar cells)
  - Cutting/scribing of Si



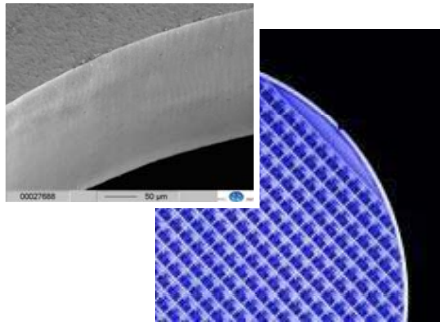
- Medical
  - Stent cutting

- Automotive
  - Drilling of injectors
  - Structuring of metal surfaces



Applications by Industries

- **Semicon**
  - **Cutting/Drilling of Si-, Ge-, GaAs-, Sa-, AlO-, AlN- Wafe**
  - **Thin-film ablation (e.g. low-k)**



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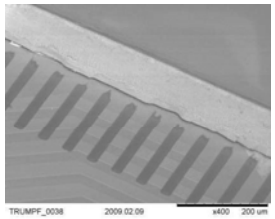

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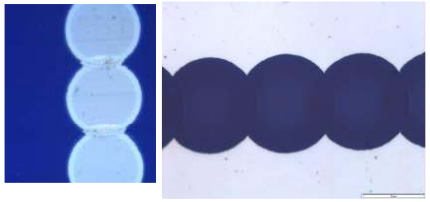

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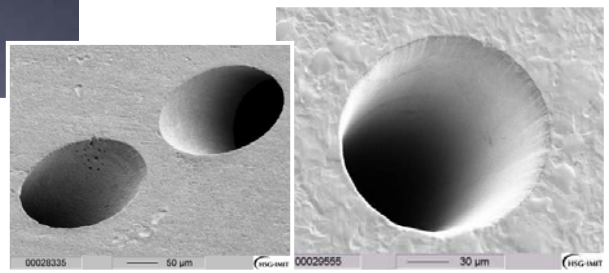
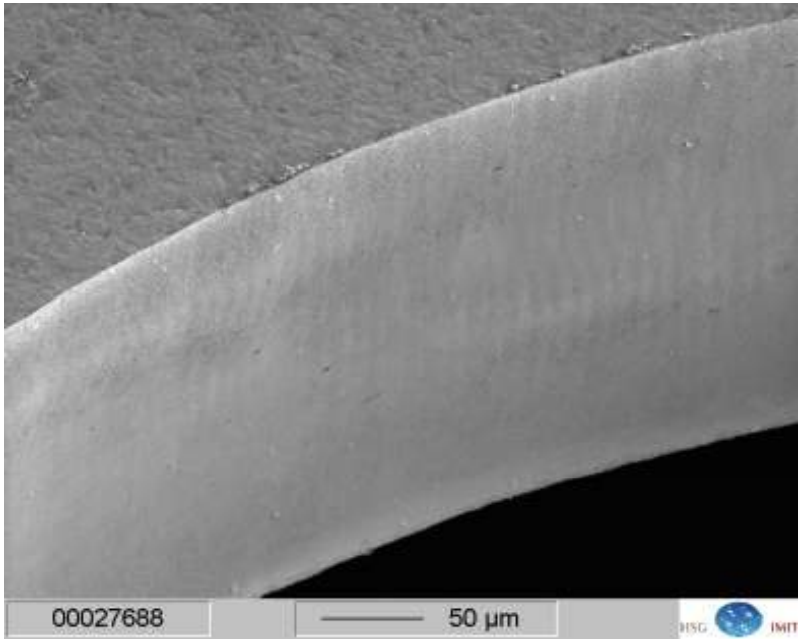


Semicon: Cutting of Silicon Wafers

Advantages:

- Small cutting kerf (< 20 µm)
- Negligible HAZ
- High quality of cutting edge
- High productivity due to high average power
- Applications: Waferdicing



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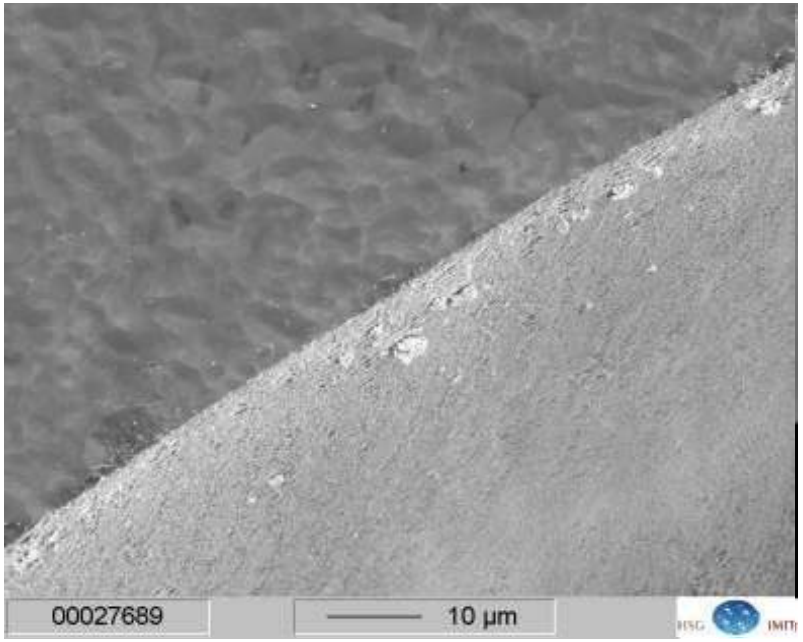
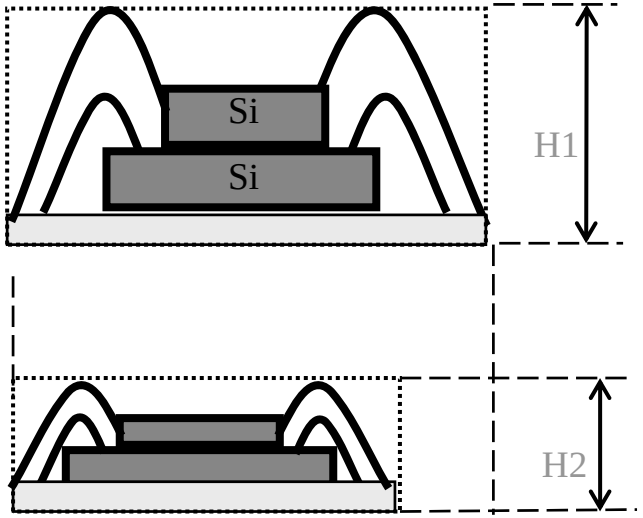


Thinning for smaller space: Why to thin?

- Reduction of thickness by half provides 50% reduction in height and 30% in footprint of packaging



- Ultra-thin Silicon gets flexible!

→Blade saw gets slow!

BUT:

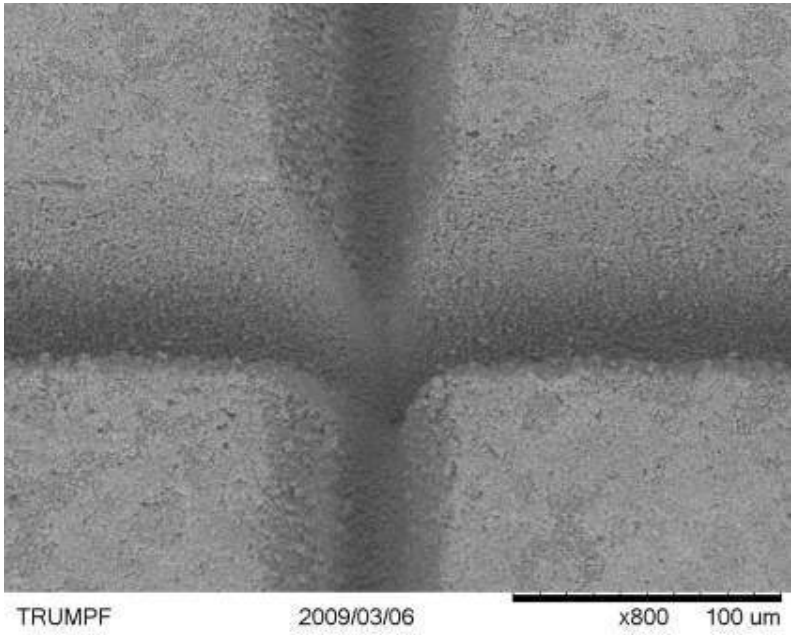
→Laser gets fast!
(100 mm/s cutting speed)

50 µm wafer.

Semicon: Cutting / Scribing of Ceramics

Advantages:

- Small kerf width (< 20 µm)
- Negligible HAZ
- High quality of cutting edge
- High productivity due to high average power
- Applications: Scribing / cutting of ceramic PCBs



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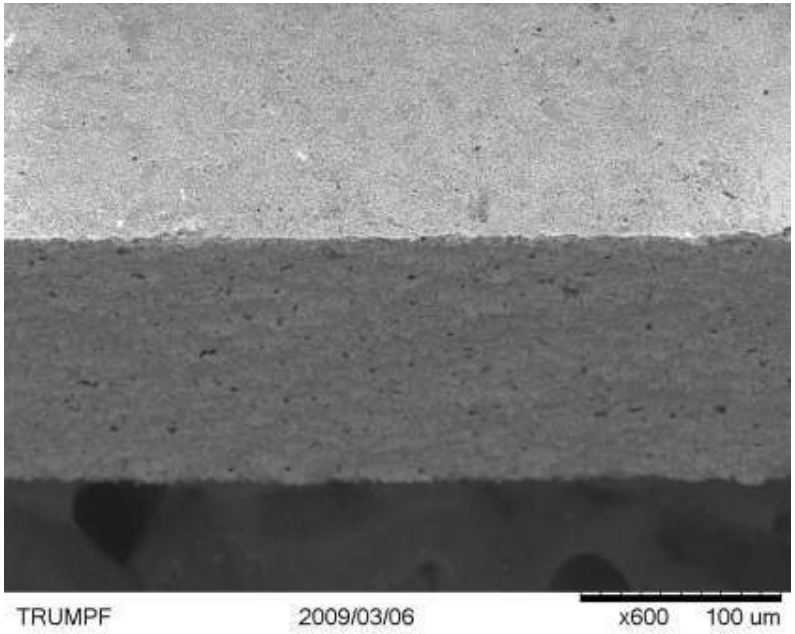

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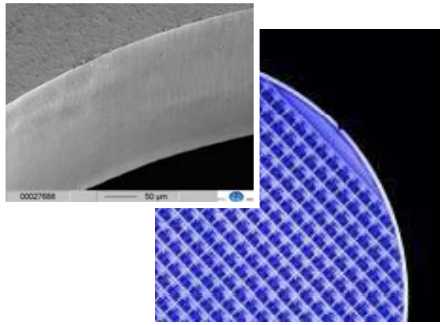
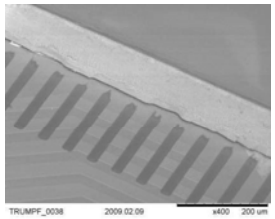


- **Flat Panel Displays**
  - **Cutting of thin glass**



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  - Thin film ablation (e.g. P1-P3 scribing for CIGS solar cells)
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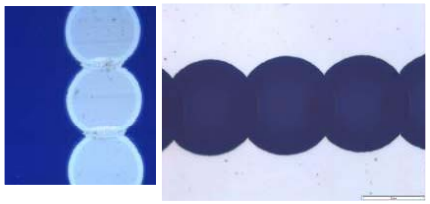
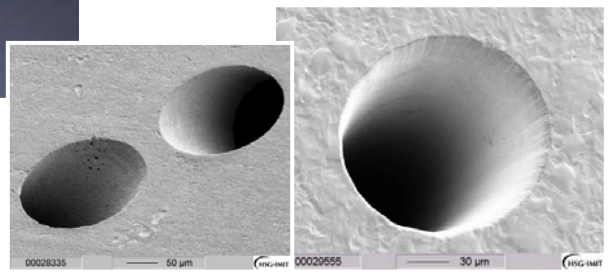


- Medical
  - Stent cutting

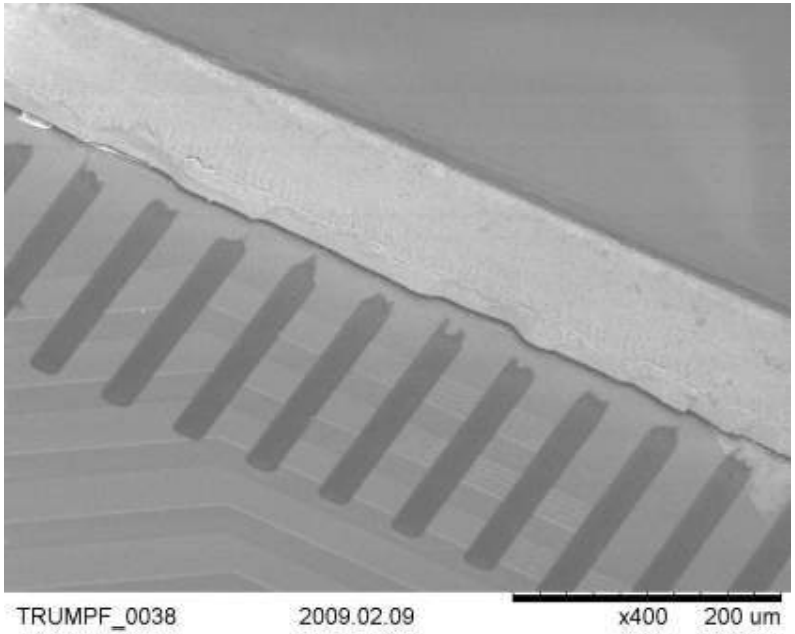
- Automotive
  - Drilling of injectors
  - Structuring of metal surfaces



FPD: Scribing and Cutting of Thin Glass

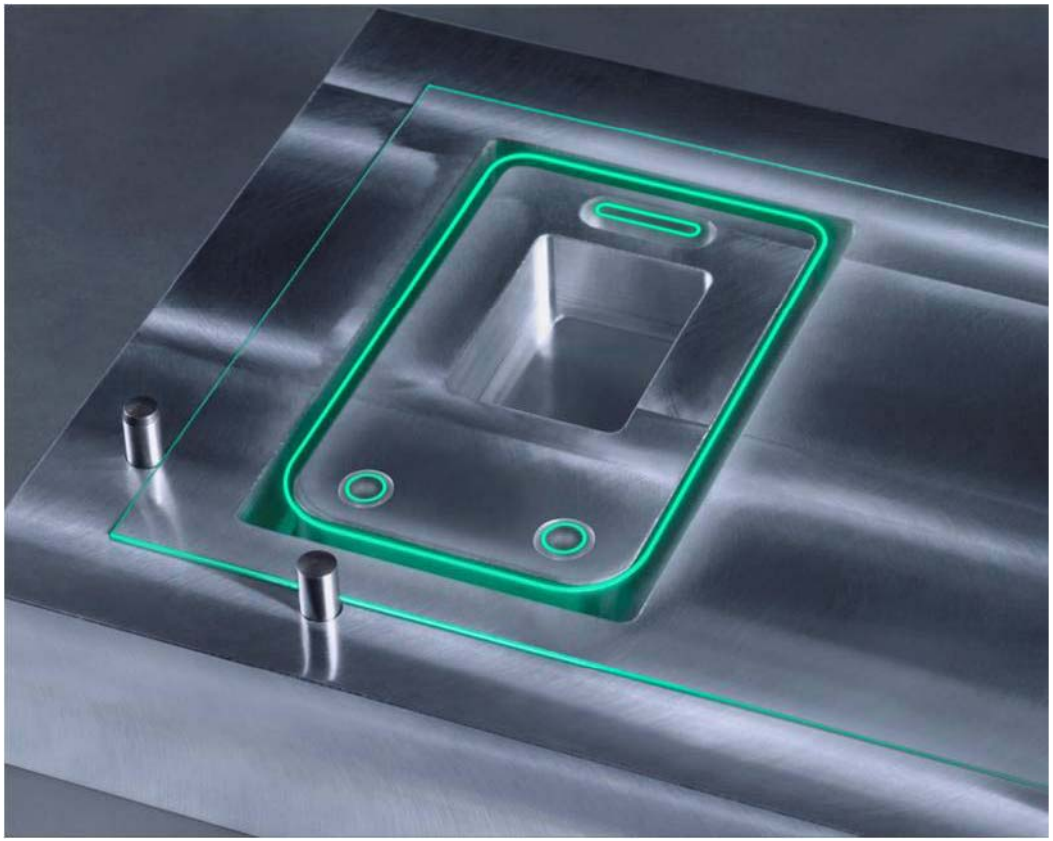
Advantages:

- Small kerf width (< 20 µm)
- Negligible HAZ
- High quality of cutting edge
- High productivity due to high average power
- Application: Scribing / cutting of thin glass for Flat-Panel-Displays



Display Glass Cutting

- Chemically strengthened glass for cover glass
One glass solution
Speaker holes
Home button
Non strengthened glass for display
Ultra-thin glass



Applications by Industries

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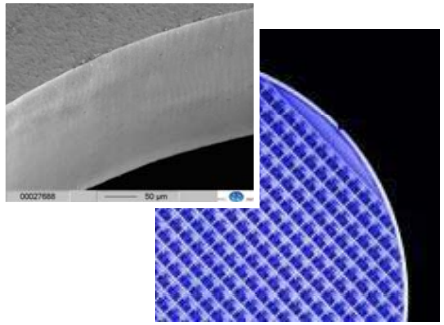
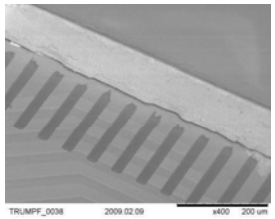
  - Cutting/Drilling of Si-, Ge-, GaAs-, Sa-, AlO-, AlN- Wafers
  - Thin-film ablation (e.g. low-k)





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  - Cutting of thin glass

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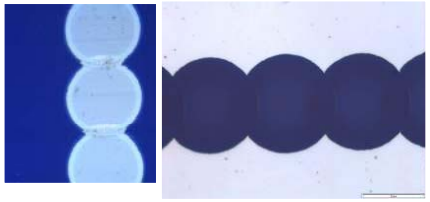
  - **Cutting/scribing of Si**



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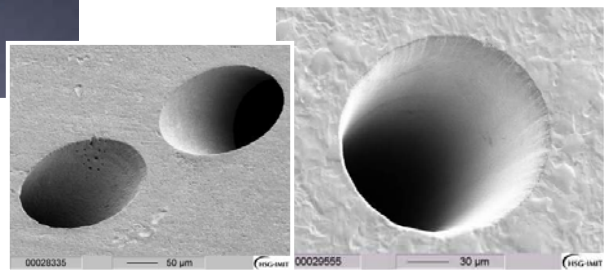
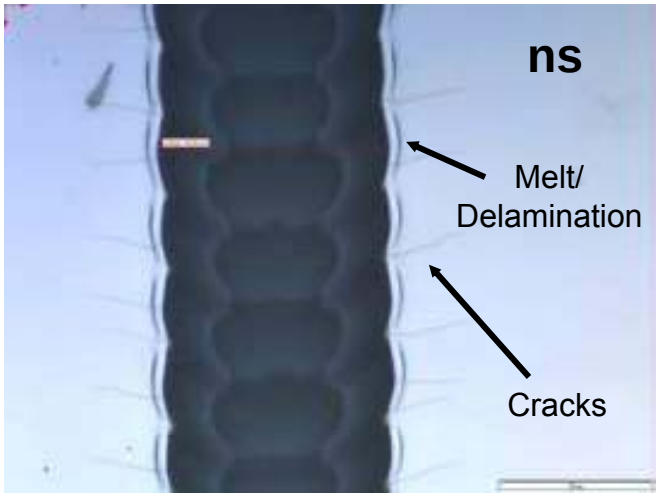
- Automotive
  - Drilling of injectors
  - Structuring of metal surfaces

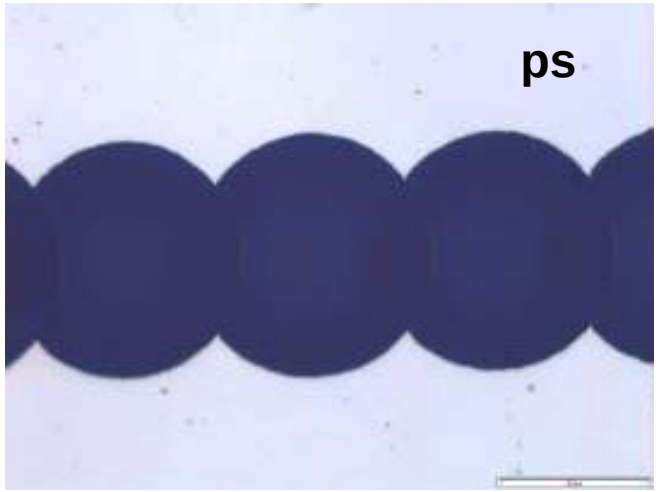


Thin Film Ablation

Laser patterning of thin Mo on glass

- Burr free
- Melt free
- No delamination
- Isolated channel
- Application: P1 step for CIGS cell connection



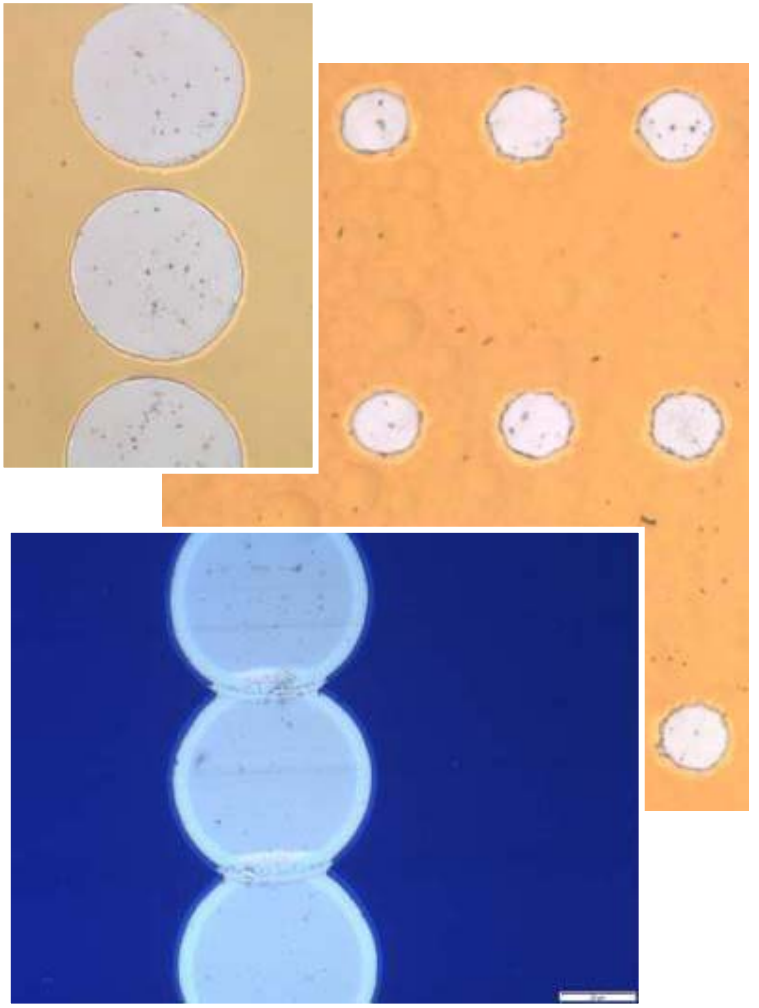


Thin Film Ablation

Laser patterning of thin films on Silicon

Direct patterning of SiO/SiN layers

- Thickness of layers: 100 nm
- Single shot ablation
- Selective removal without affecting base material (Silicon)
- Application: Cell connection for Silicon solar cells, low-k dielectric grooving

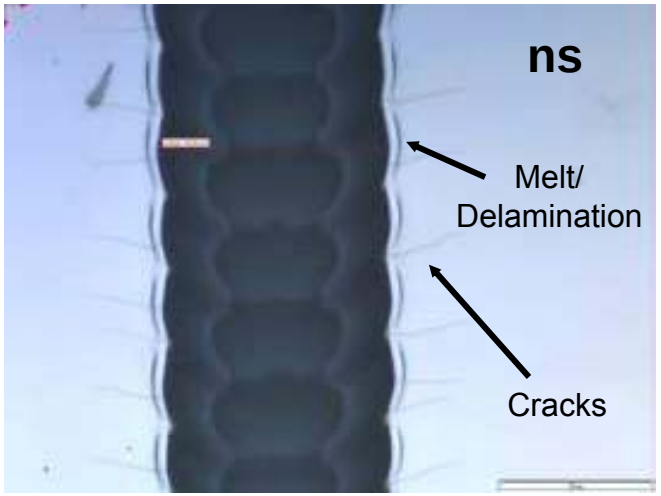


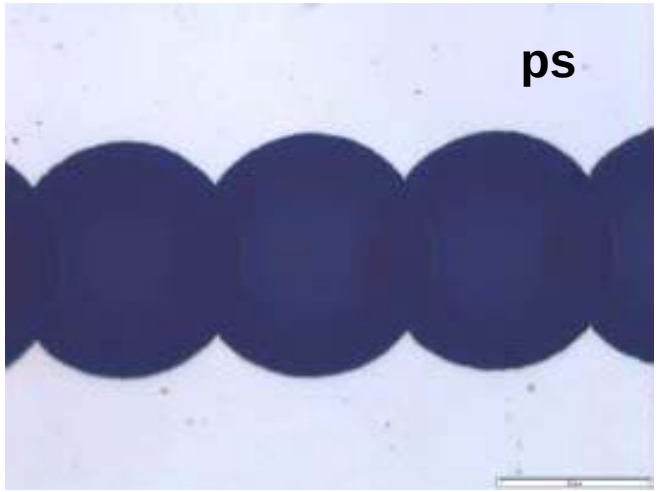
PV: Thin Film Ablation

Laser patterning of thin Mo on glass

- Advantages:
  - Negligible burr
  - Negligible melt
  - No delamination
  - High speed (> 4 m/s)

- Application: P1 step for CIGS cell connection



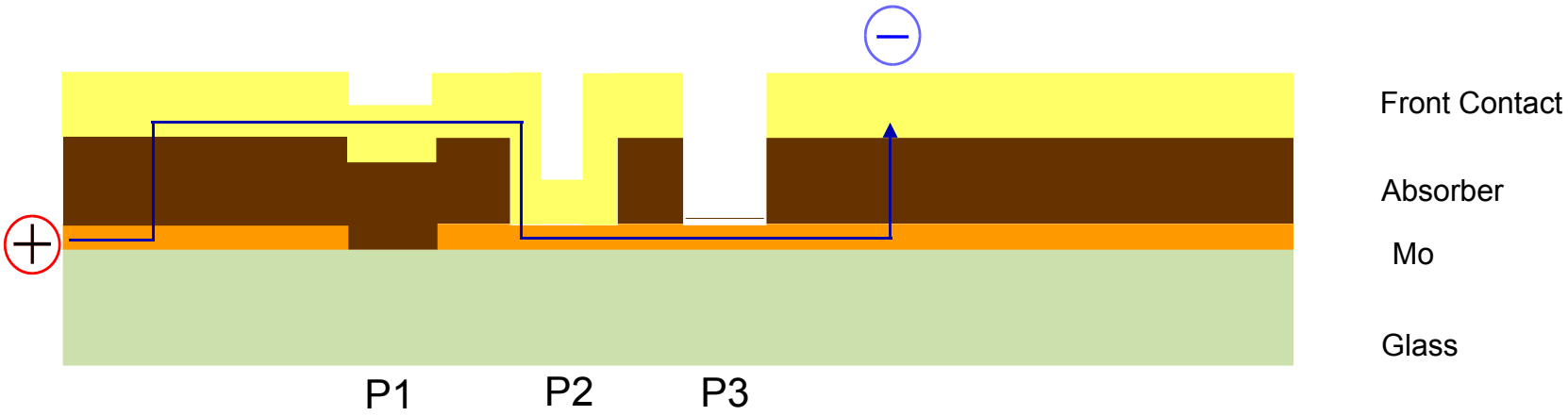


Patterning of CIGS Solar Cells

- P1: Patterning of back contact (Molybdenum)
- P2: Patterning of absorber (CIGS)
- P3: Patterning of front contact and absorber

→ Connection of cells on a module

Advantage laser vs. mechanical scribe: Reduced „dead area“ → higher efficiency



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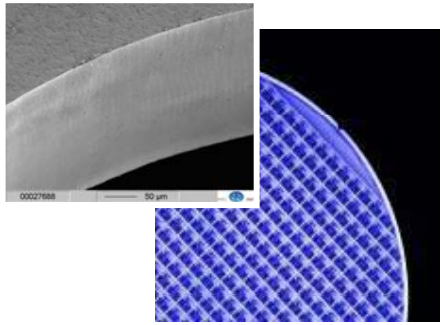

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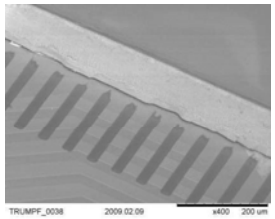

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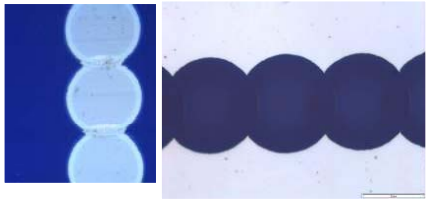

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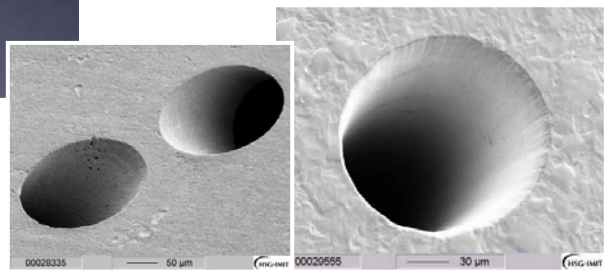
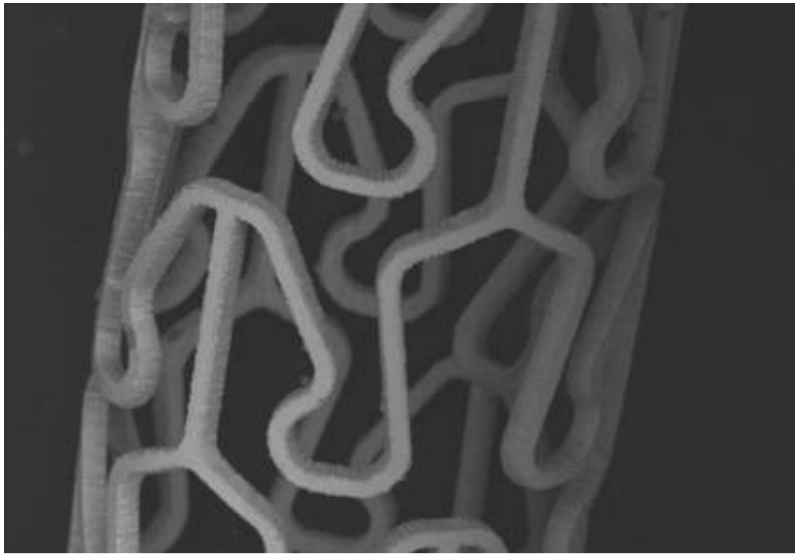


Cutting with picosecond pulses

Cutting of Nitinol

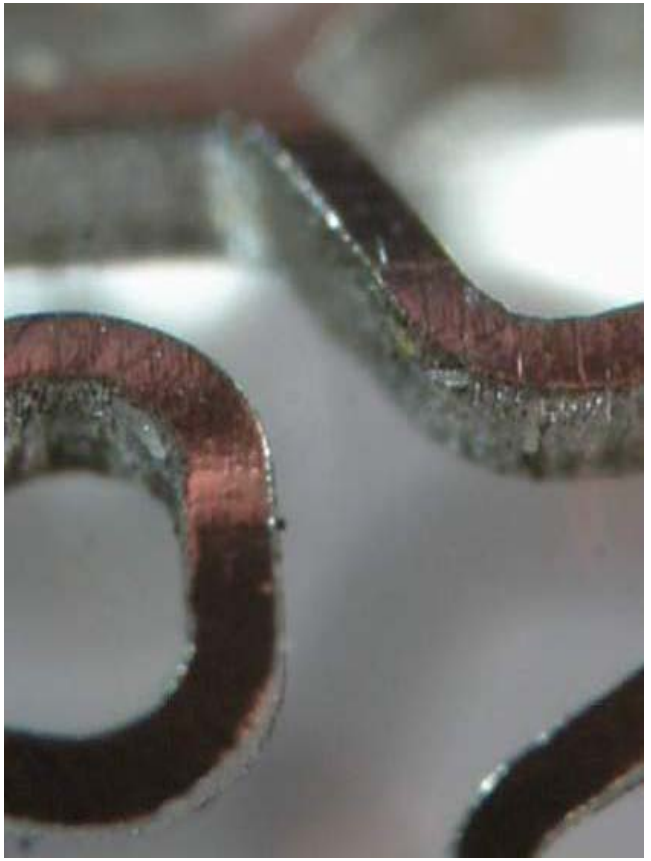
- Small cutting kerf (< 10-20 µm)
- Negligible HAZ
- High quality of cutting edge
- No electro polishing!
- High yield
- High productivity due to high average power
- Application: Cutting of Stents, endoscopes



State-of-the-art Stent Cutting

- Fusion cutting with single mode fiber lasers
  - Output power 50 to 200 W (typically 100 W)
  - Modulation: cw to 50 kHz
  - Cutting optics
- Cutting result
  - Thermal cutting process
  - Burr formation
  - Heat affected zones
  - Spillings (metal splatters)

⇨Expensive reworking required
  - mostly by hand

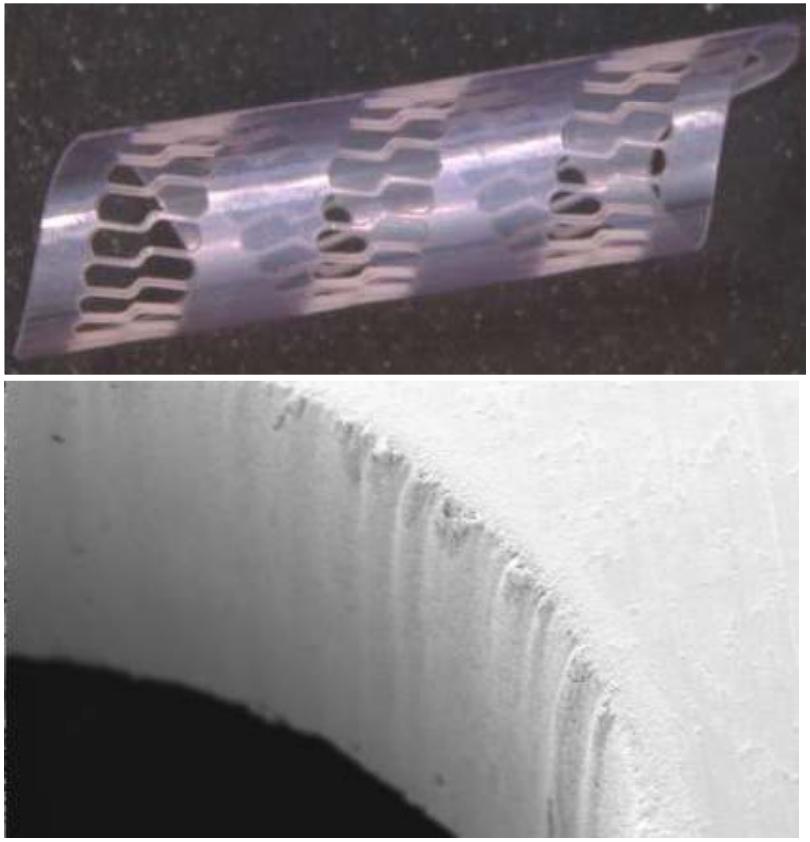


Stent Cutting with TruMicro Series 5000

- Highest quality cutting process
  - Negligible burr formation
  - Negligible HAZ

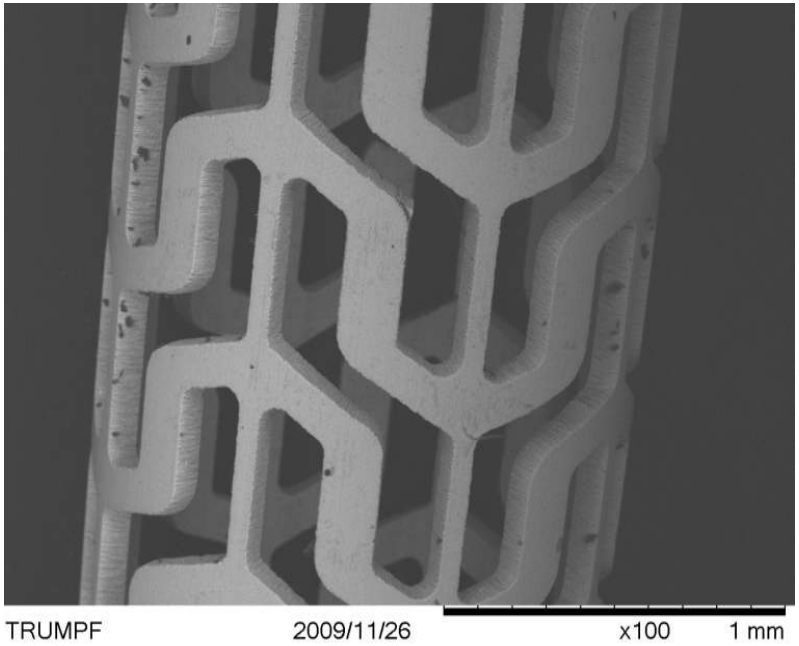
- Materials (e.g.):
  - CrCo
  - Nitinol
  - Polymers
  - Absorbable materials

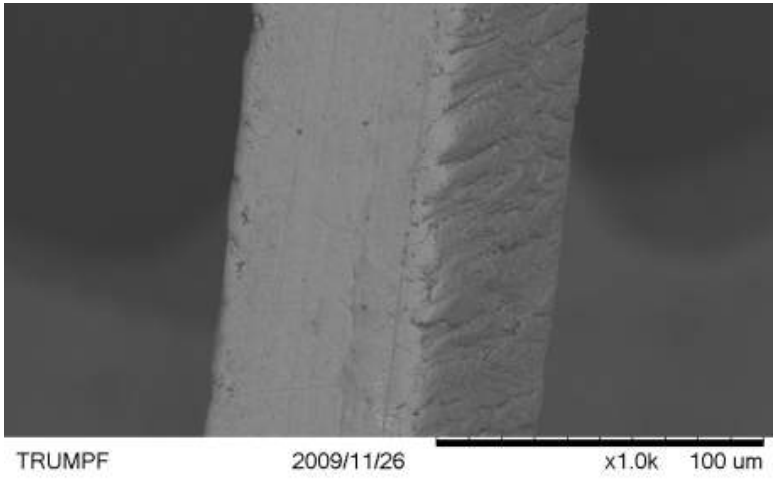
⇨ Reduction of scrap at the beginning of the process chain
⇨ Saving of expensive materials
⇨ Saving of expensive finishing processes



SEM Pictures (1)

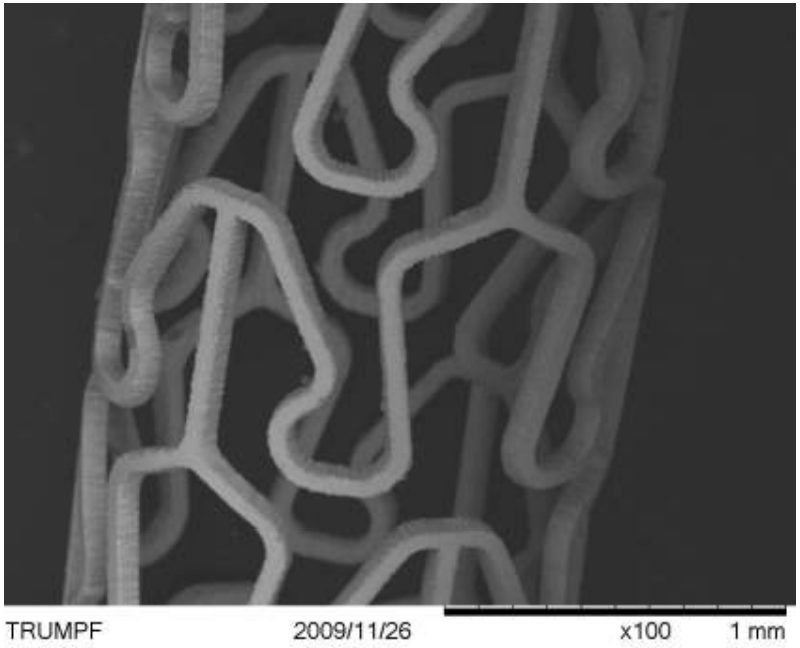
CoCr

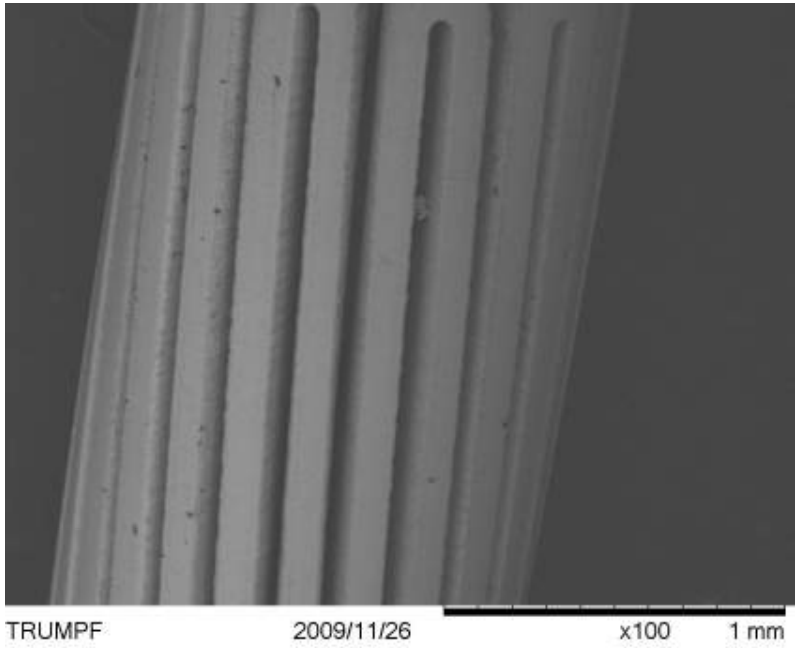




SEM Pictures (2)

Nitinol





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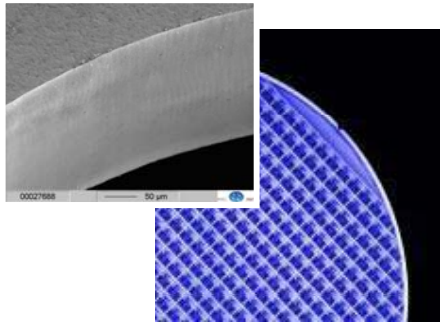

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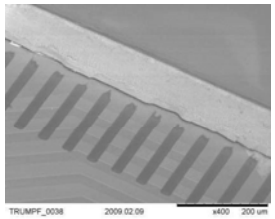

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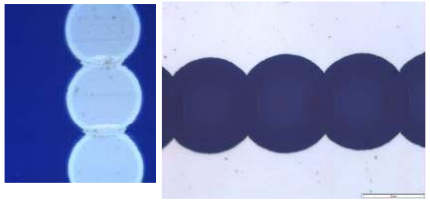

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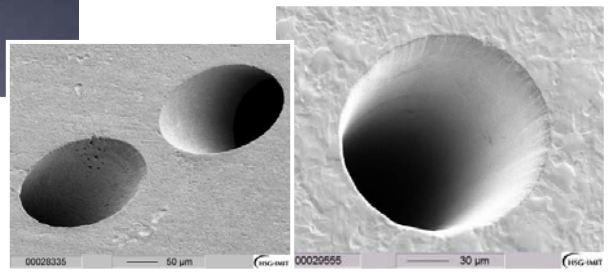
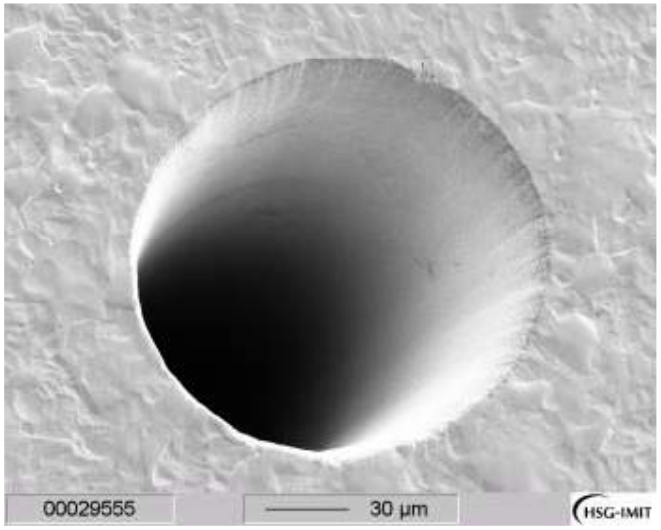
  - **Drilling of injectors**
  - **Structuring of metal surfaces**



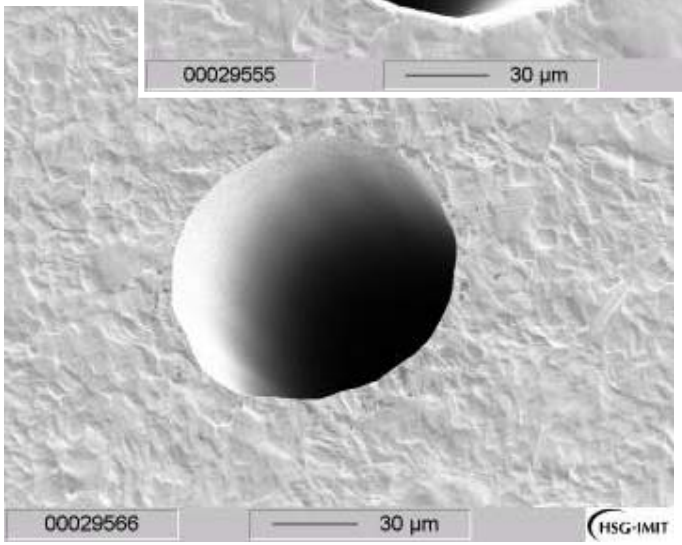
Drilling with high Aspect Ratio

Helical Drilling of Metal
No melt or debris
No Heat Affected Zone
Free selection of taper (positive, negative or zero)

- Diameters: 50 to 100 µm
- Material thickness: up to 2 mm
- Applications: cooling holes for turbine blades



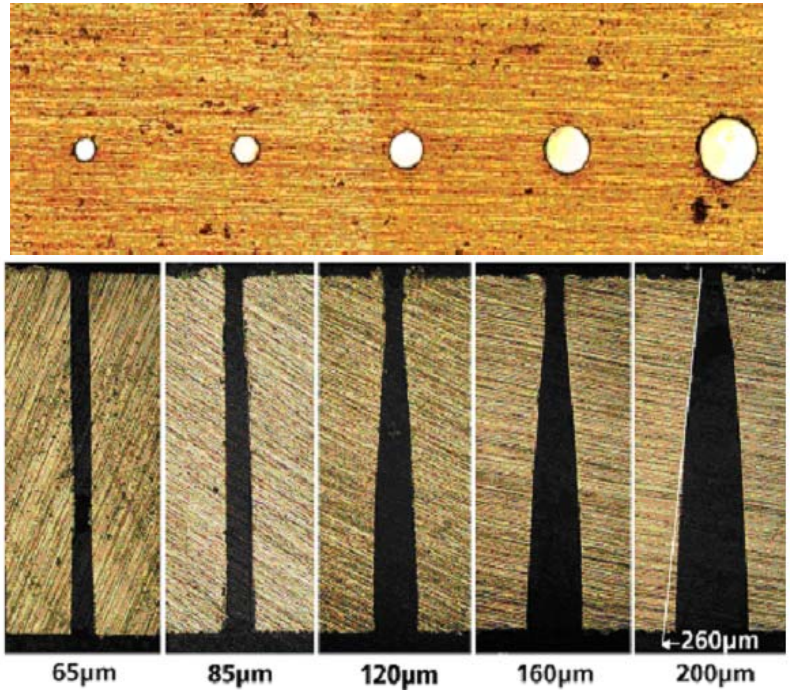
Entrance



Exit

Successful application - Injector drilling

Material: Stainless Steel
Thickness: 1mm
Min. Diameter: 50um
Aspect ratio: 1 : 20
Roundness of the hole: > 95%
Surface quality: No burr
Production speed: 1s/hole
Laser: TruMicro 5250
Technology: helical drilling



Structuring with Picosecond Pulses

Structuring of tribological surfaces

Advantage TruMicro 5050:

- Burr free processing
- No postprocessing required
- High throughput due to high average power and repetition rate
- Applications: cylinder bore, punching tools, piston, …

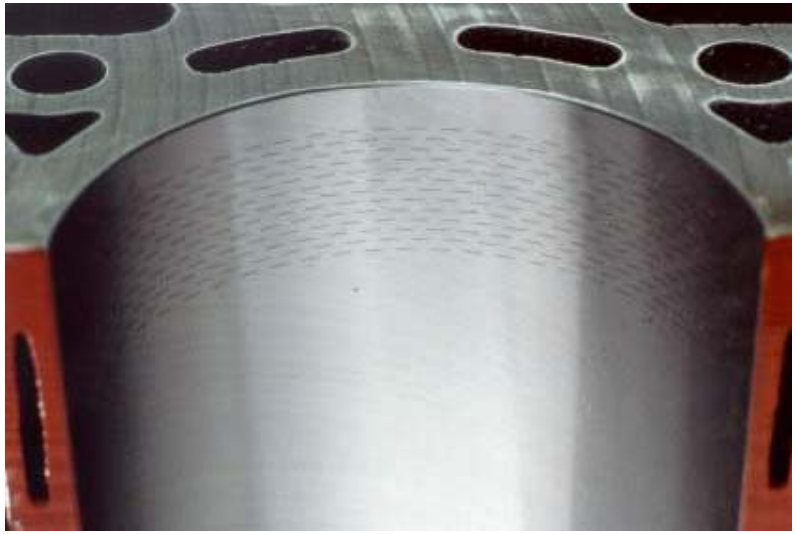
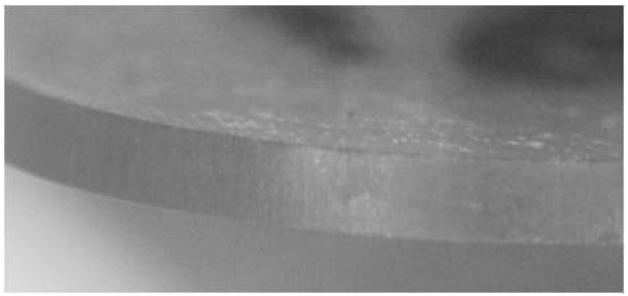
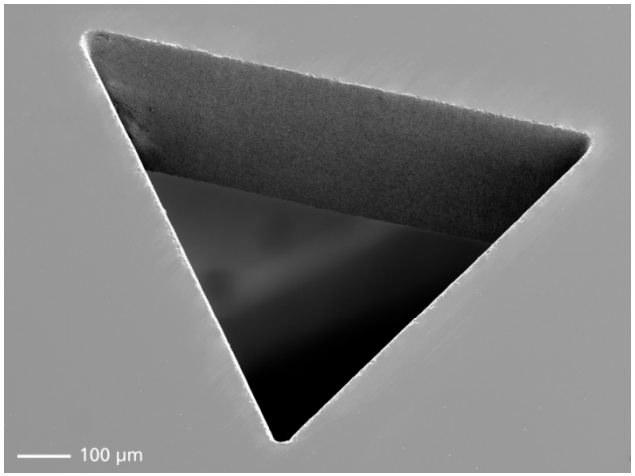


Foto: Gehring

Cutting of Sapphire

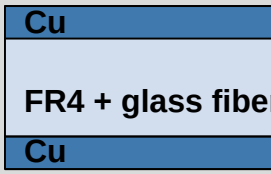


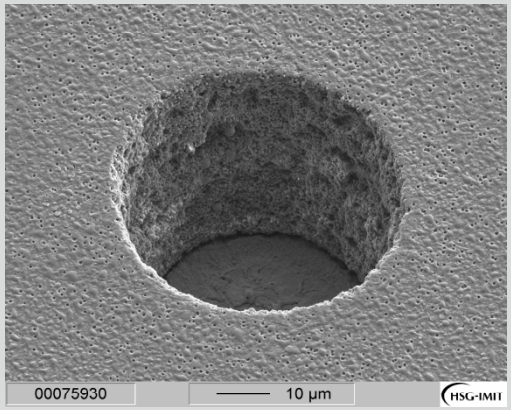
- 0.4 mm Sapphire Wafer
- Smallest feature size 0.2 mm
- ~5 s per small disc

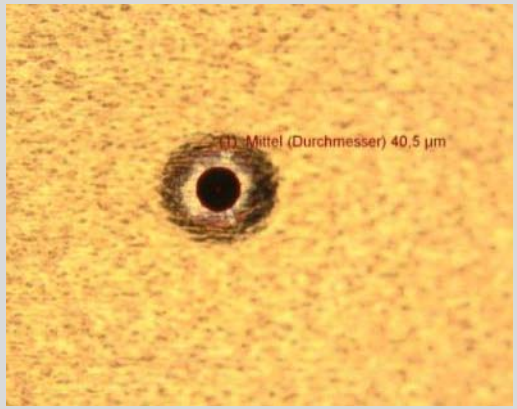


Drilling of PCBs PCB钻孔

- Vias and blind holes down to copper layer
  盲孔和通孔
- IR picosecond laser
  红外皮秒
- Percussion drilling
  脉冲冲击钻孔
- 40 µm diameter
  直径40微米
- ~1 ms drilling time per hole
  每孔一个毫秒
- high repeatability
  高重复性

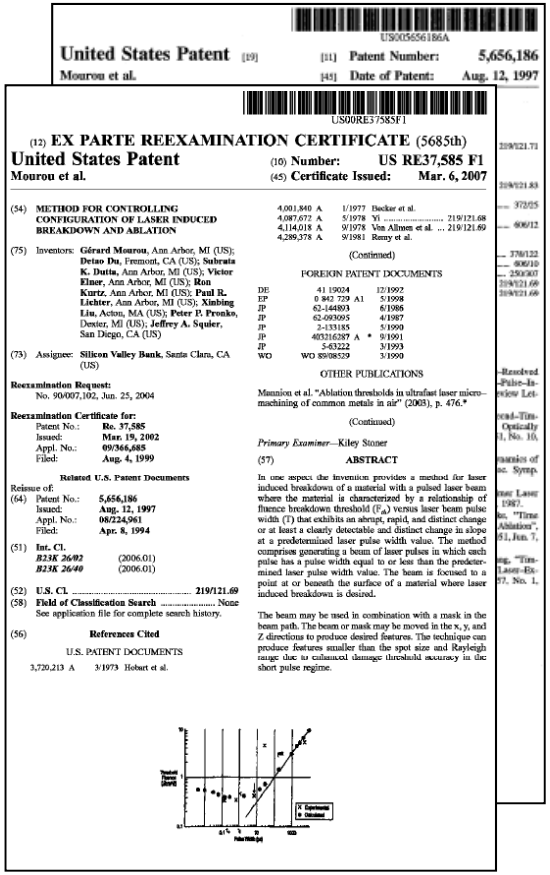






Patents for Ultrafast Machining

- U.S. patent Nr. 5,656,186 protects cold machining with ultrashort laser pulses (< 10 ps)
- The patent was **unsuccessfully challenged** in 2007
- US-patent valid until 2014, outside the US until 2015
- **TRUMPF** holds a non exclusive **license** which is **transferable** to its customers



US005656186A

United States Patent [19]
Mourou et al.

[11] Patent Number: 5,656,186
[45] Date of Patent: Aug. 12, 1997

US00RE37585F1

(12) **EX PARTE REEXAMINATION CERTIFICATE** (5685th)
United States Patent
Mourou et al.

(10) Number: US RE37,585 F1
(45) Certificate Issued: Mar. 6, 2007

(54) **METHOD FOR CONTROLLING CONFIGURATION OF LASER INDUCED BREAKDOWN AND ABLATION**

(75) Inventors: **Gérard Mourou**, Ann Arbor, MI (US); **Detao Du**, Fremont, CA (US); **Subrata K. Dutta**, Ann Arbor, MI (US); **Victor Elner**, Ann Arbor, MI (US); **Ron Kurtz**, Ann Arbor, MI (US); **Paul R. Lichter**, Ann Arbor, MI (US); **Xinbing Liu**, Acton, MA (US); **Peter P. Pronko**, Dexter, MI (US); **Jeffrey A. Squier**, San Diego, CA (US)

(73) Assignee: **Silicon Valley Bank**, Santa Clara, CA (US)

Reexamination Request:
No. 90/007,102, Jun. 25, 2004

Reexamination Certificate for:
Patent No.: **Re. 37,585**
Issued: **Mar. 19, 2002**
Appl. No.: **09/366,685**
Filed: **Aug. 4, 1999**

Related U.S. Patent Documents
Reissue of:
(64) Patent No.: **5,656,186**
Issued: **Aug. 12, 1997**
Appl. No.: **08/224,961**
Filed: **Apr. 8, 1994**

(51) **Int. Cl.**
B23K 26/02 (2006.01)
B23K 26/40 (2006.01)

(52) **U.S. Cl.** **219/121.69**
(58) **Field of Classification Search** ..... None
See application file for complete search history.

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WO WO 89/08529 3/1990

OTHER PUBLICATIONS
Mannion et al. "Ablation thresholds in ultrafast laser micro-machining of common metals in air" (2003), p. 476.*
(Continued)

Primary Examiner—Kiley Stoner

(57) **ABSTRACT**

In one aspect the invention provides a method for laser induced breakdown of a material with a pulsed laser beam where the material is characterized by a relationship of fluence breakdown threshold (F_{th}) versus laser beam pulse width (T) that exhibits an abrupt, rapid, and distinct change or at least a clearly detectable and distinct change in slope at a predetermined laser pulse width value. The method comprises generating a beam of laser pulses in which each pulse has a pulse width equal to or less than the predetermined laser pulse width value. The beam is focused to a point at or beneath the surface of a material where laser induced breakdown is desired.

The beam may be used in combination with a mask in the beam path. The beam or mask may be moved in the x, y, and Z directions to produce desired features. The technique can produce features smaller than the spot size and Rayleigh range due to enhanced damage threshold accuracy in the short pulse regime.

TruMicro Series 5000 (compact)

High performance micro-machining with small footprint and low cost

Thank You!
谢谢大家！

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蔡伟军
电话：13913591512
邮箱：william.cai@cn.trumpf.com