Ultrafast beam deflection for efficient picosecond laser processing

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Outline

- Introduction Time-Bandwidth Products
- Ultrafast laser processing
- Discussion Polygon-mirror line scanner
- Processing results
- Outlook

Introduction Time-Bandwidth Products

- Spin-off ETH Zurich, commercial ultrafast products since 1996
- Since January 2014 wholly-owned by JDSU
- "SESAM®" know-how technology-leader
- International sales-network, established in all key markets
- Established products for industrial "24/7" applications
- Industrial customers in markets such as semiconductor, biotech, material-processing in general, etc.

Material removal with a Gaussian beam

- Material removal rate

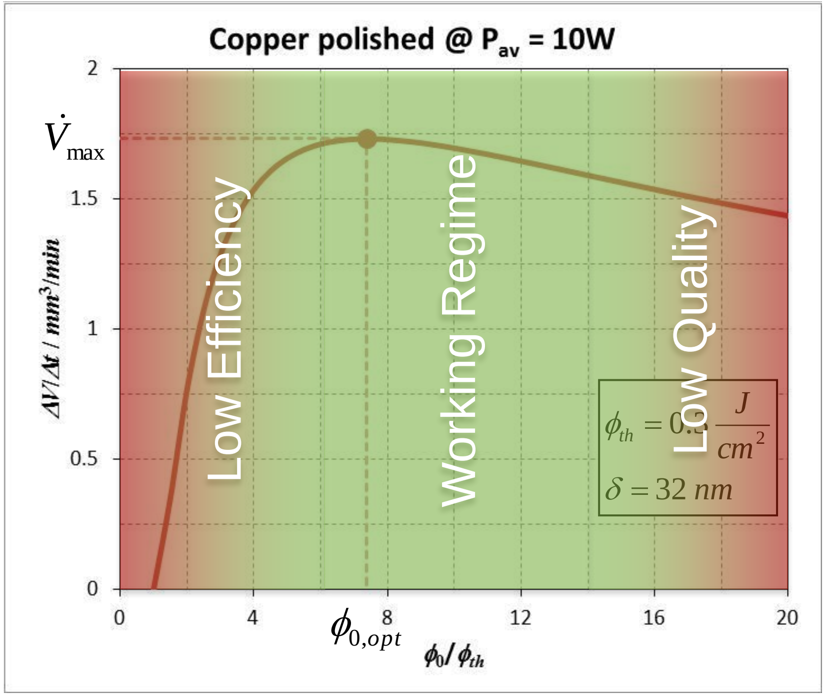
$$z_{abl} = \delta \cdot \ln\left(\frac{\phi_0}{\phi_{th}}\right) \quad \Rightarrow \quad \frac{\dot{V}}{P_{av}} = \frac{1}{2} \cdot \frac{\delta}{\phi_0} \cdot \ln^2\left(\frac{\phi_0}{\phi_{th}}\right)$$

With:
ϕ_{th}: threshold fluence:
δ : energy penetration depth

ϕ_0 : peak fluence $\quad \phi_0 = \frac{2 \cdot E_P}{\pi \cdot w_0^2}$

- Optimum point / maximum removal rate

$$\phi_{0,opt} = e^2 \cdot \phi_{th} \qquad \frac{\dot{V}_{max}}{P_{av}} = \frac{2}{e^2} \cdot \frac{\delta}{\phi_{th}}$$



- Rough rule of thumb: Choose a peak fluence between 6 and 14 times ϕ_{th}.

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High throughput micro-machining

Optimum fluence / pulse energy maximizing ablation efficiency ⟷ **optimum repetition rate for a fixed average power**

depending on ↓

Threshold fluence | Penetration depth | Incubation effects

depending on ↓

Material | Wave length | Pulse duration

optimum repetition rate for a fixed average power ↓

Increasing average power ↓

Increase repetition rate ↓

Increased productivity

High throughput micro-machining

Options for material processing with high average power:

- Power-sharing (multiple processing sites, diffractive optical elements) ➔ **OK** (need lots of equipment, limited, highly specilized applications)
- High pulse energy (if rep.-rate is fixed) ➔ **inefficient**
- High repetition rate (with fix, opt. pulse energy) ➔ **most efficient**

BUT:
large pulse overlap,
leading to thermal side-effects
(heat accumulation)

Vector-based processing with Galvo-scanners

Today: systems limited by scanner performance

Assume:

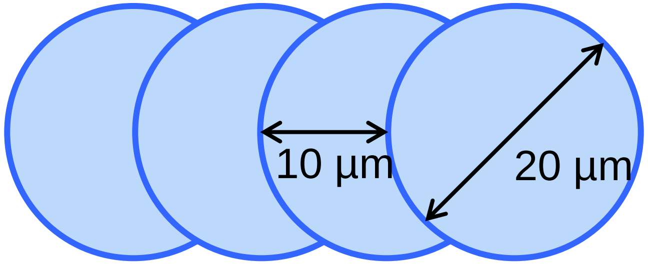
- Spot diameter (IR): 20 µm
- Lateral pulse overlap of 50%: 10 µm
- Pulse repetition rate: 8 ~~1~~ MHz (with increasing average power, keeping pulse energy constant)

➔ Required lateral scan-speed: 80 ~~10~~ **m/s**

Today's commercial systems: **3-5 m/s** (e.g. with 100 mm f-Θ)

Pulse-overlap >98%,

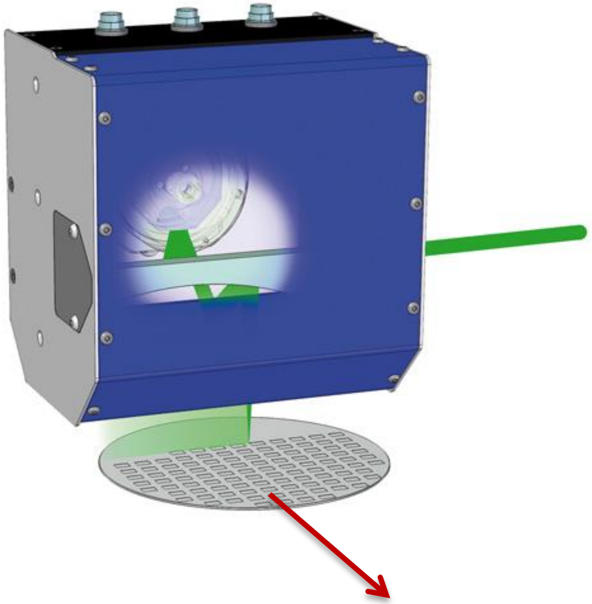
thermal side-effects !



Potential solution: high-speed line scanners

Example: Next Scan Technology LSE170

- Lateral spot velocity: 25-100 m/s
- Adressable area: 170 mm x ∞
- F-Θ (telecentric): f=190 mm
- Input aperture: 10 mm
  - Min. spot diam. ($1/e^2, M^2=1.1$) 56 µm (IR)
    28 µm (green)
- Position-accuracy: 5 µm
- Repeatability: 3 µm
- Data-format: Bitmap

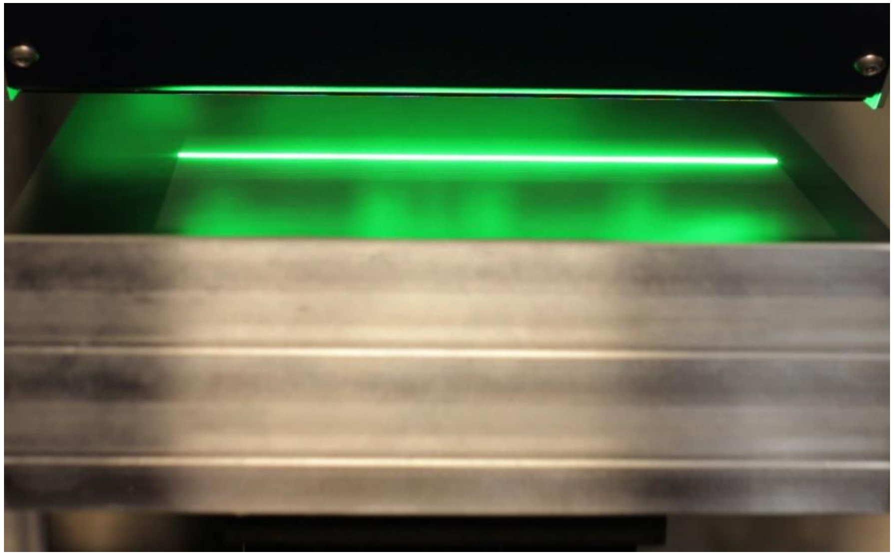


High-speed line scanners

No universal technology, but good for large business-fields:

- Surface texturing
- Flat panels / touch-screens
- "Roll-to-roll" patterning
- Wafer-dicing
- Large area structures with high complexity

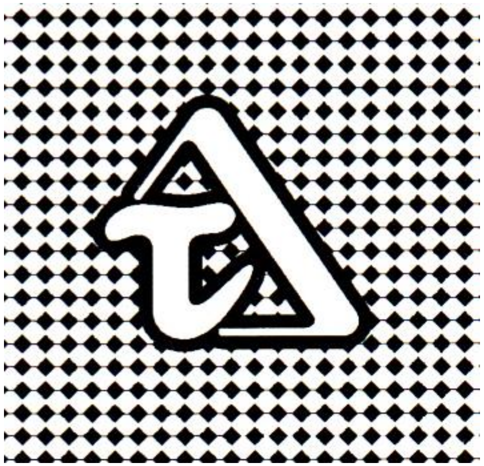
→ *"complexity is for free"*

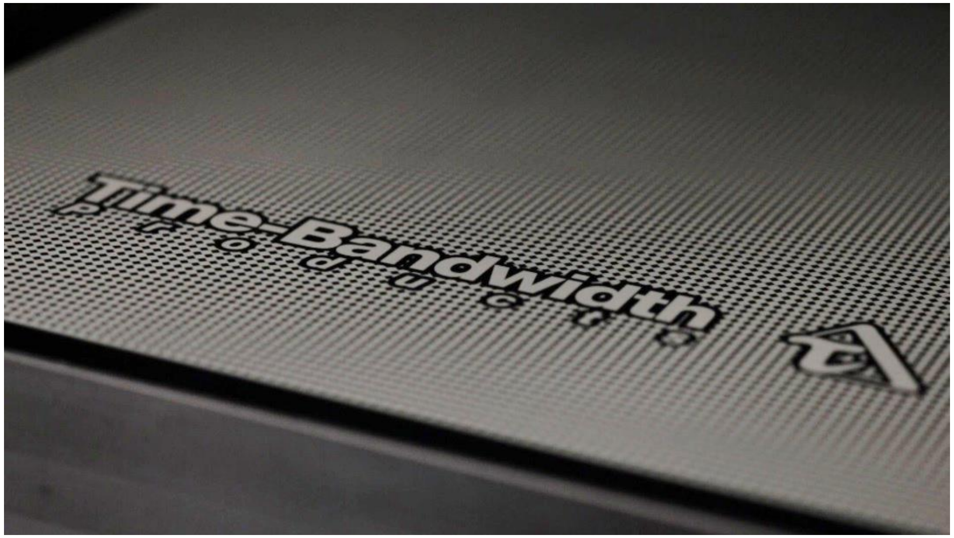


Ultrafast processing with Polygon-scanners

Example: large-area structuring

- Pulse-frequency: 2 MHz
- Area: 170 x 170 mm^2 (14500 segments, 1x1mm^2)
- Time: 10s (resolution-dependent)
- 400 lines/s

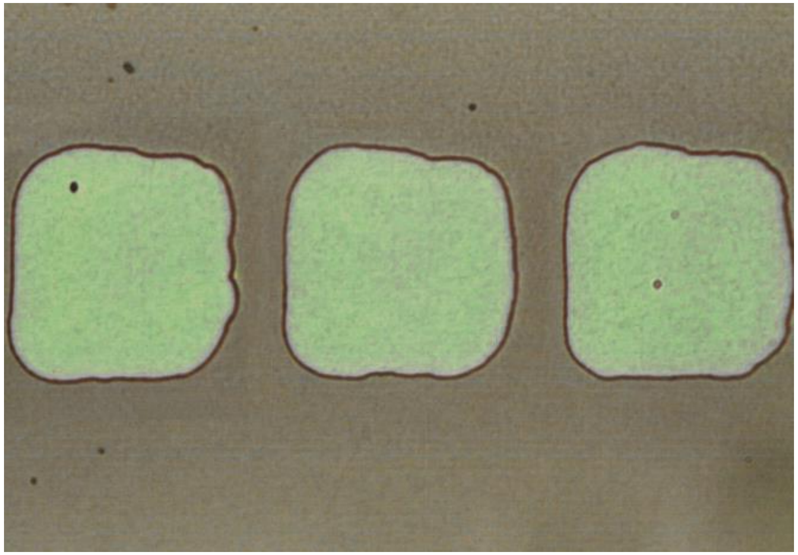




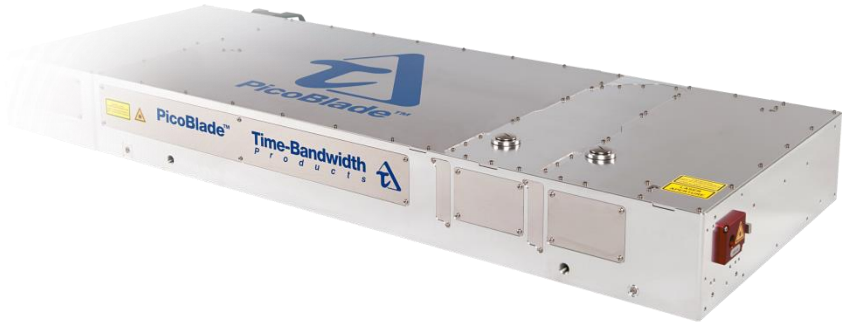
Example: ITO-removal with square flattop-profile

- Pulse-frequency: 6 MHz
- Edge length of focus: 30 µm
- Overlap: 60% (=18 µm pitch)

→ *Lateral scanning speed:* ***108 m/s***



OEM Laser for micro-materialprocessing



Laser requirements

Assume:

- Spot diameter: 50 µm (IR, f=190 mm f-theta)
- Overlap: 0 – 75% (full pulse separation – good surface quality)
- Full scanning speed: 100 m/s

50 µm pitch (0% overlap): **2 MHz**

12.5 µm pitch (75% overlap): **8 MHz**

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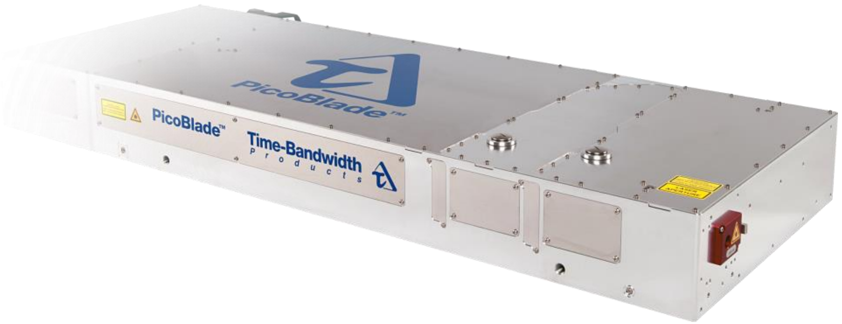
PicoBlade™

fully integrated picosecond laser



Average power	up to 50 W
Pulse-frequency	single-pulse to 8 MHz
Pulse-energy	up to 200 µJ
Pulsewidth	10 ps
Peakpower	up to 20 MW
Wavelength	1064 nm
M^2	< 1.3

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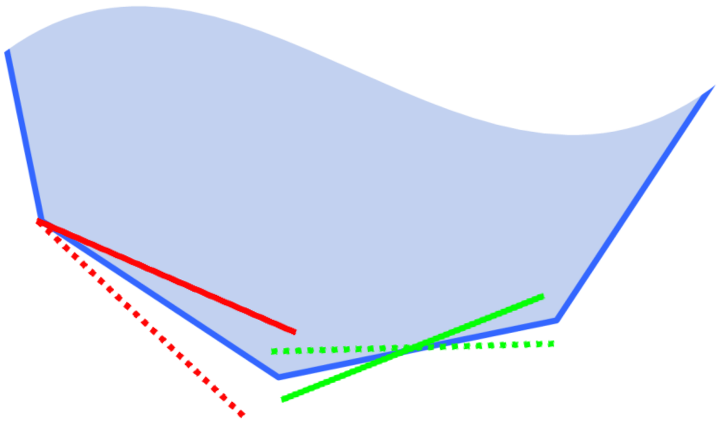
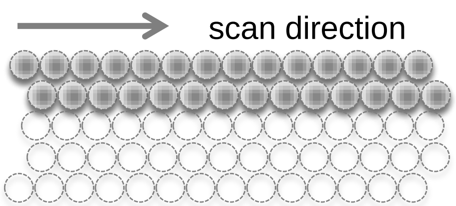
Geometric polygon errors

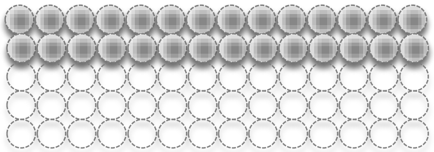


Facette angular offset / displacement

- Marking result:



- Solution: compensating with *SuperSync*^{TM} technology (not trivial for modelocked lasers)

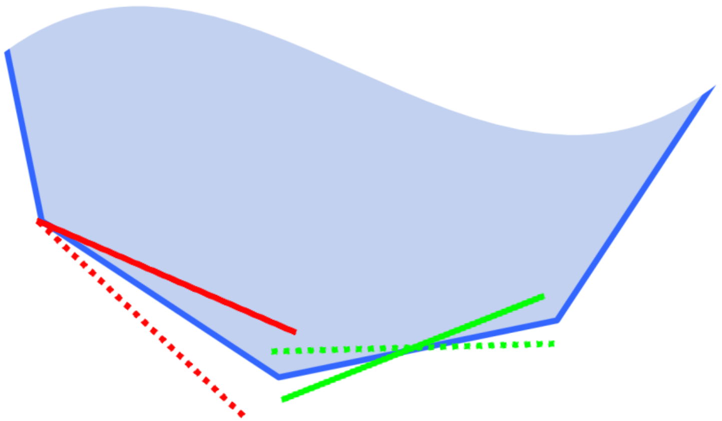


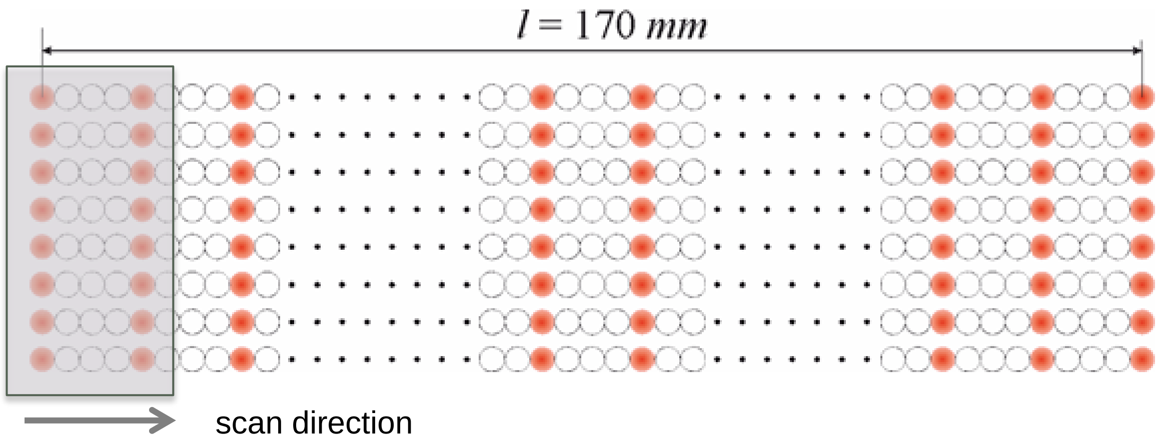
Position accuracy

Geometric polygon errors

Facette angular offset / displacement

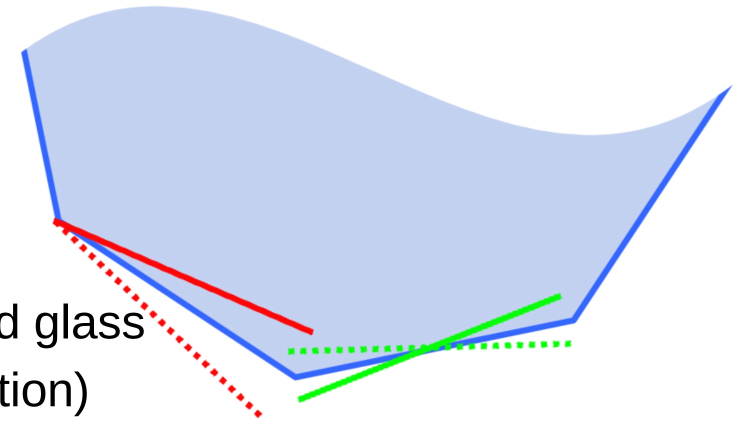
- Experiment:





Position accuracy

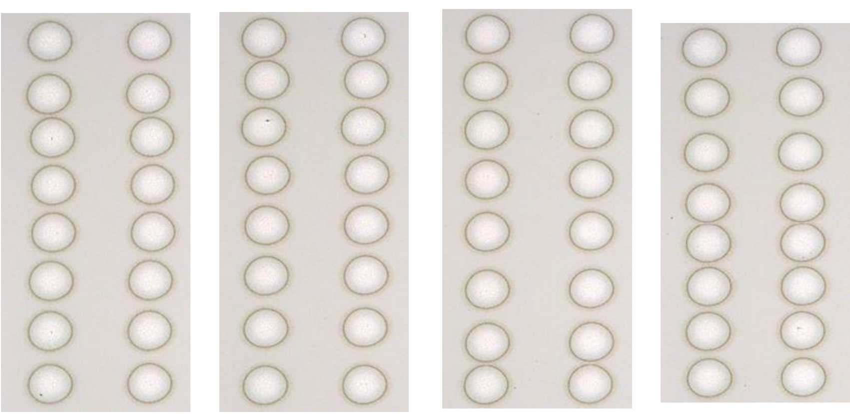
Geometric polygon errors



Facette angular offset / displacement

- f=2 MHz, w_0=28 µm
- Marking single spots on chromium coated glass
- Pitch: kept constant, 100 µm (pixel-selection)

25m/s 50m/s 70m/s 95m/s

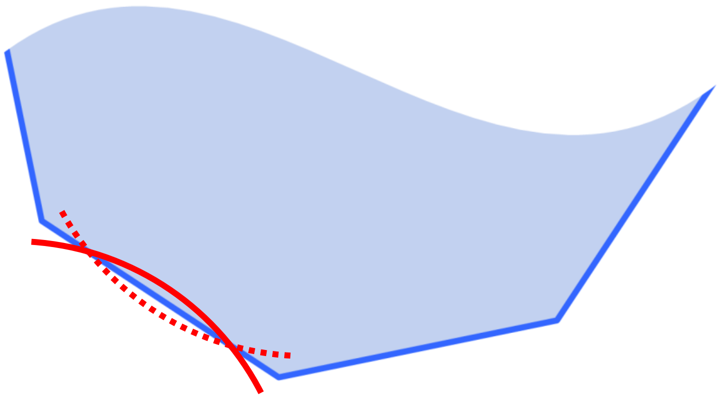


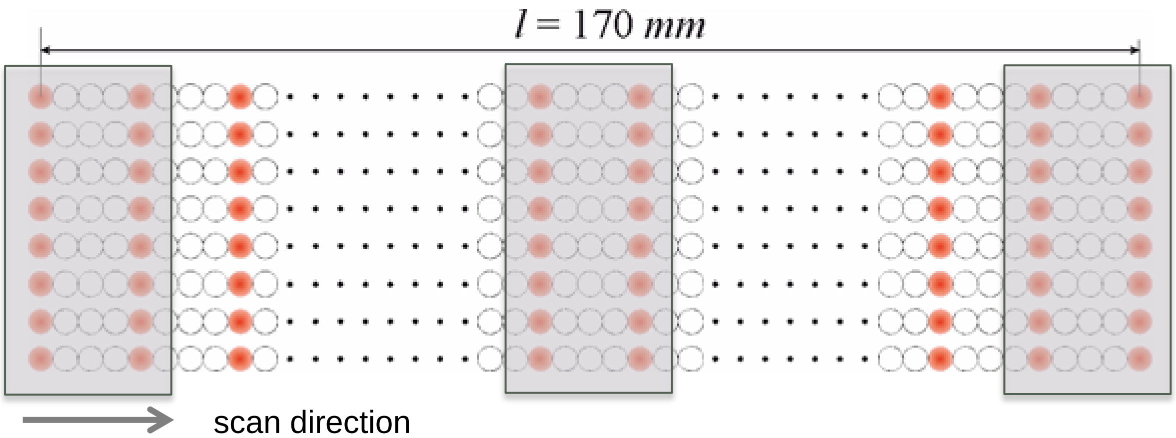
scan direction

Geometric polygon errors

Facette distortions

- Experiment

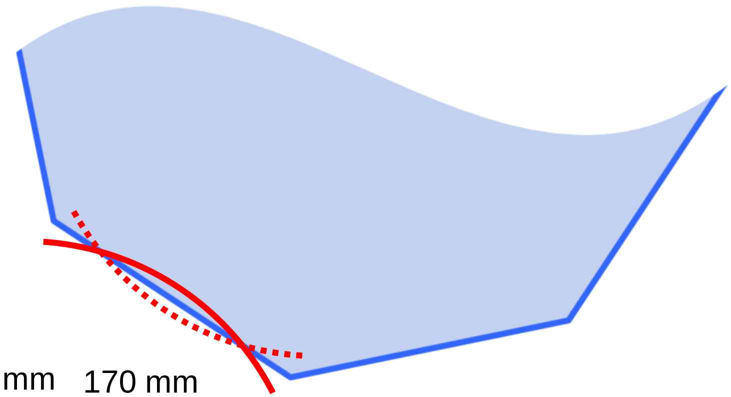


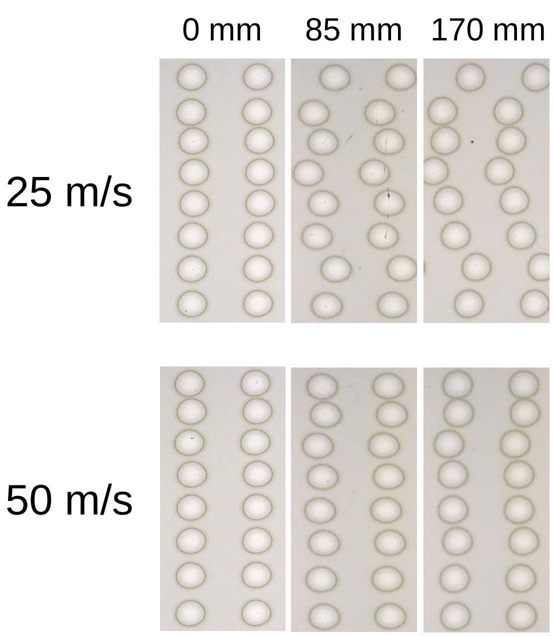


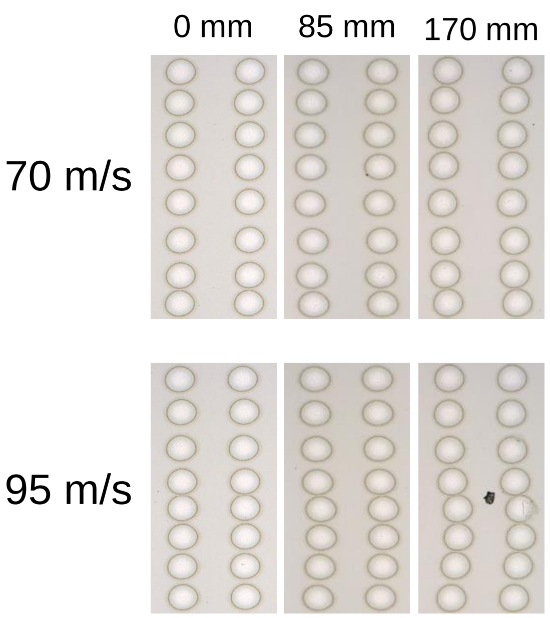
Position accuracy

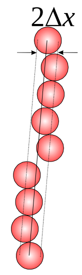
Geometric polygon errors

Facette distortions









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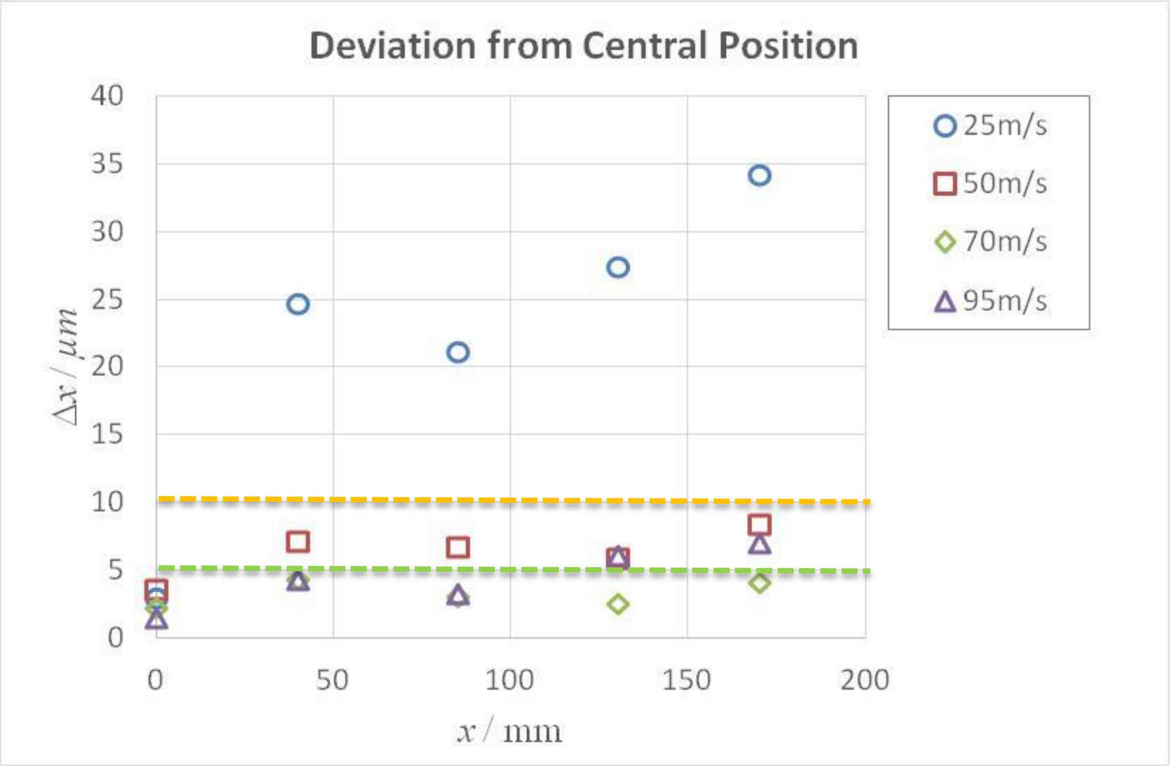
Position accuracy



- Strong deviations for 25m/s.
- Not proportional to increasing distance to start position.
- Accuracy better than ±10µm for 50m/s.
- Accuracy almost within ±5µm
  for 70 and 95m/s.

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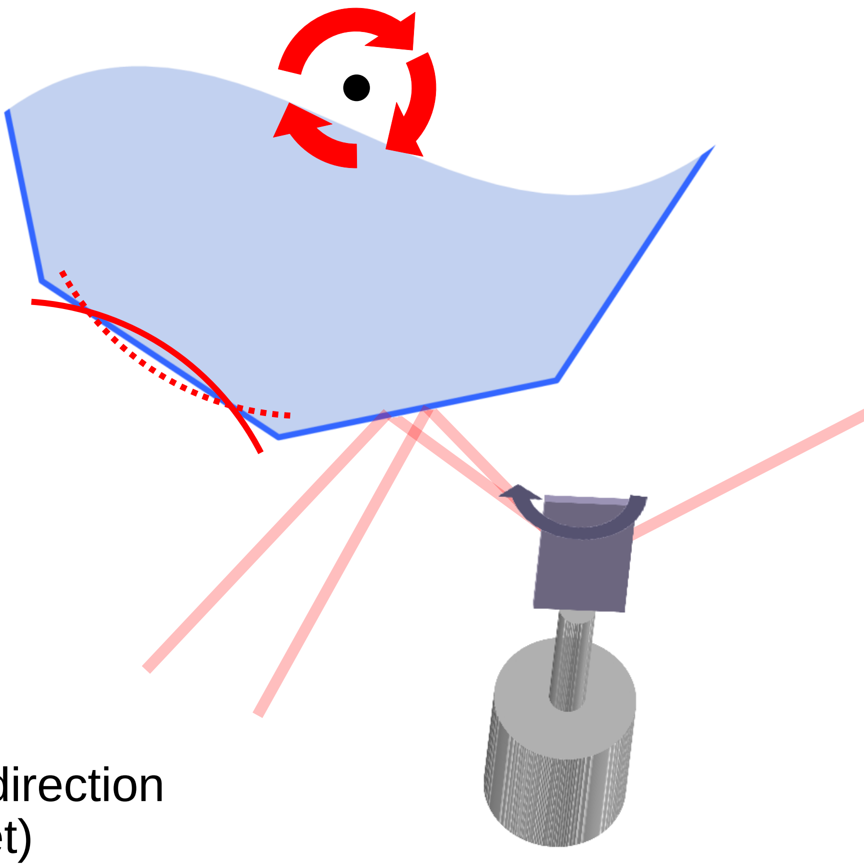
Position accuracy

Geometric polygon errors

Facette distortions



Plus:

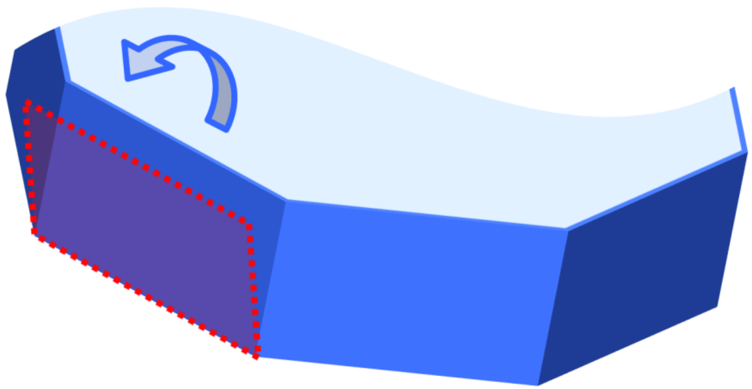
- Stabilization of rotation
- (F-theta distortions)

- Solution:
  - Better motion controller
  - Additional, fast deflector in scanning direction (can also correct facette angular offset)

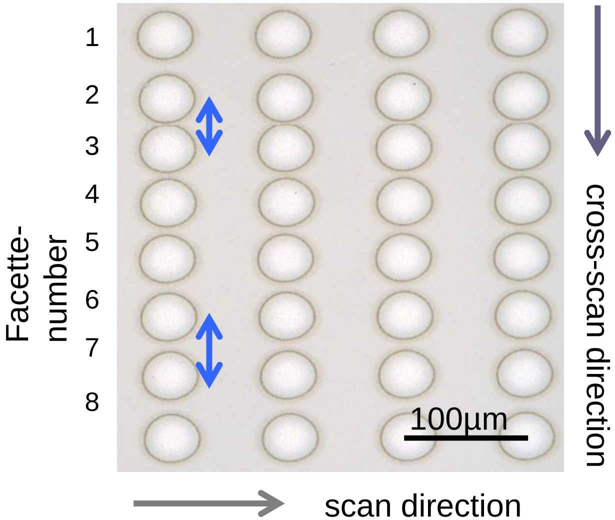
Position accuracy

Geometric polygon errors

Pyramidal-error

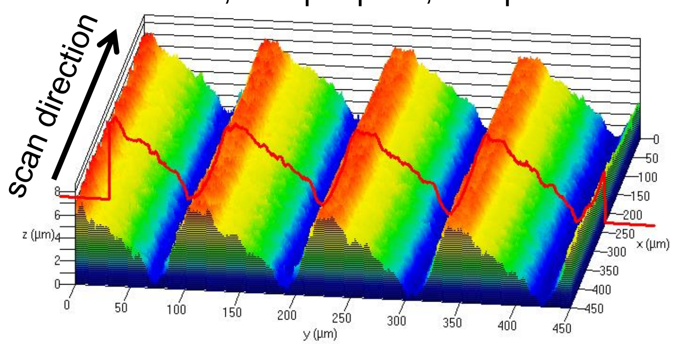


2MHz, 95m/s

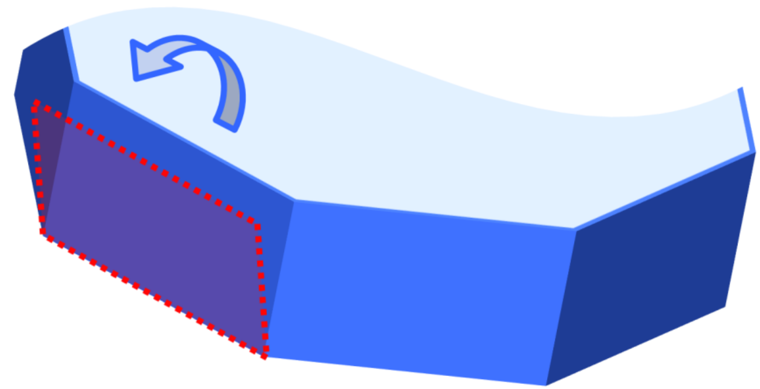


- Variable line-pitch in cross-scan direction
- uneven surface for engraving-applications / multiple passes:

2MHz, 14.5µm pitch, 200 passes

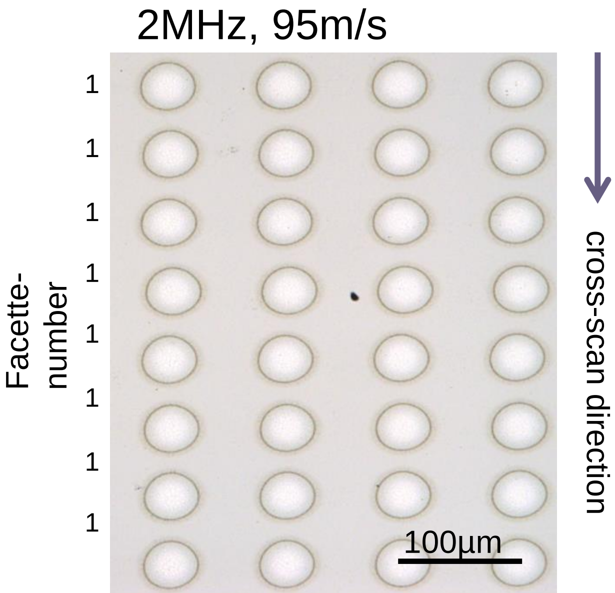


Position accuracy

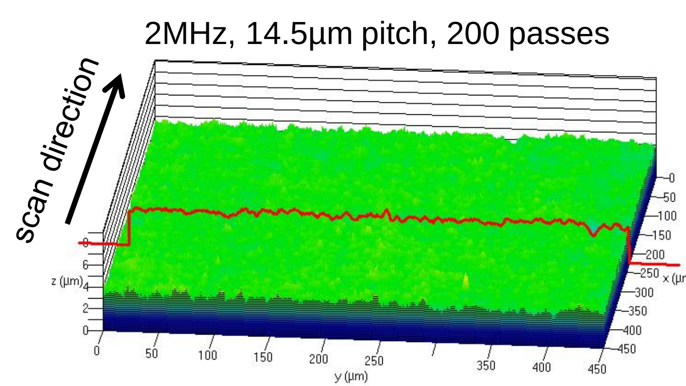


Geometric polygon errors

Pyramidal-error



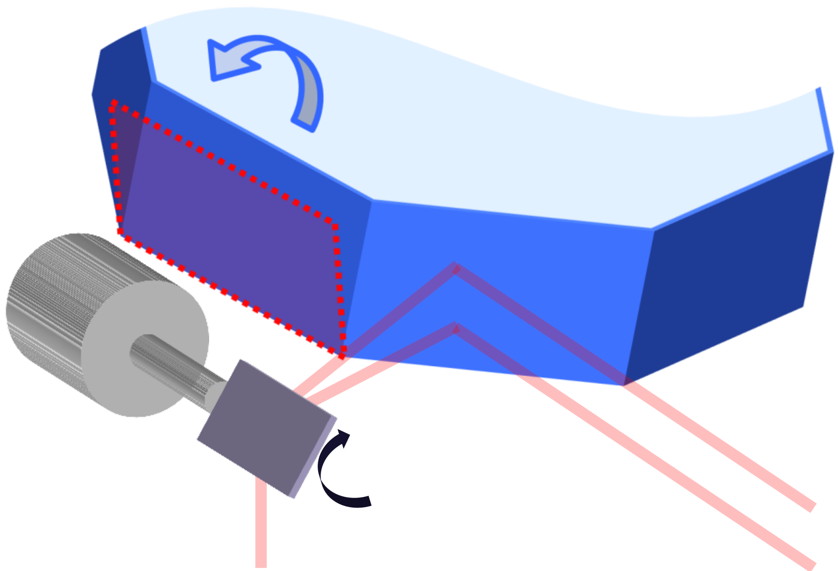
- Using single facette gives constant pitch
- Smooth surface



Position accuracy

Geometric polygon errors

Pyramidal-error

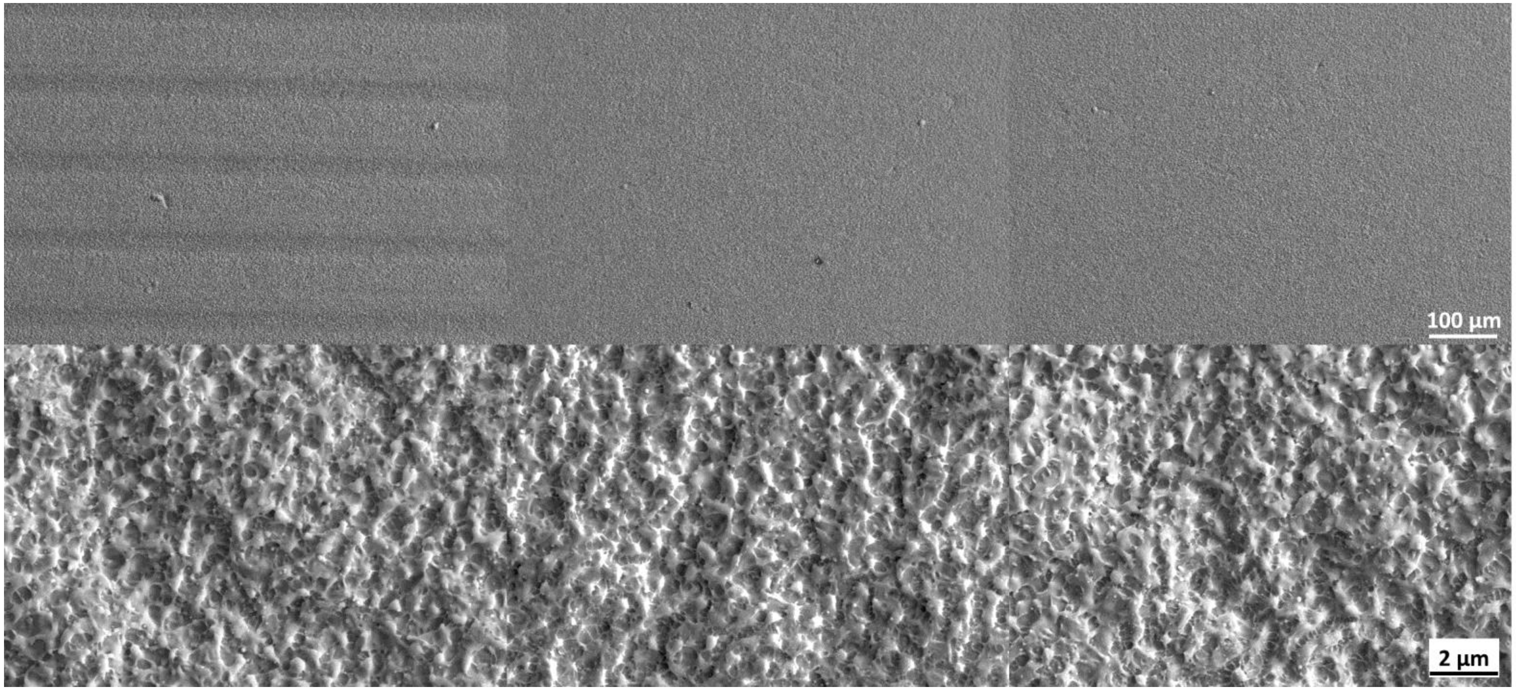


- Solution:
  - Using single facet → processing 8 times slower
  - Averaging pyramidal error → works only for multi-pass, increases minimum feature size
  - Additional fast deflector in cross-scan direction

Comparison of different machining strategies

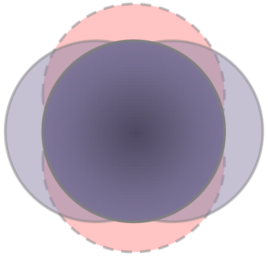
Ablation at 2 MHz in stainless steel with 200 layers

Normal 1 Facet Averaging



Scanned spot-pattern vs. fixed spot

- Spot-pattern on Si-wafer, n-times; λ = 532 nm, f_{rep} = 2 MHz, v= 70 m/s

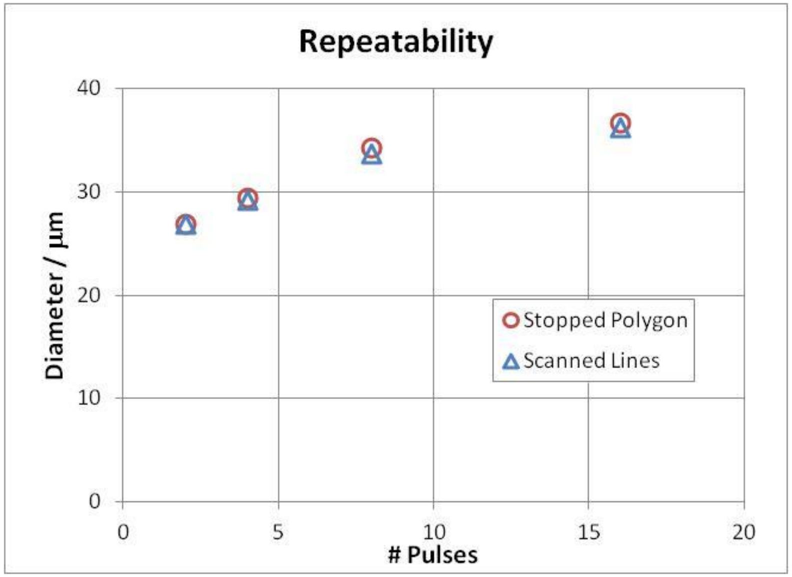


→ Incubation-effects!

- Fixed spot, n-times; f_{rep} = 200 kHz (=line-frequency)

Result:

- Max. deviation < 600 nm
- Repeatability @ 70 m/s: better ± 1 µm



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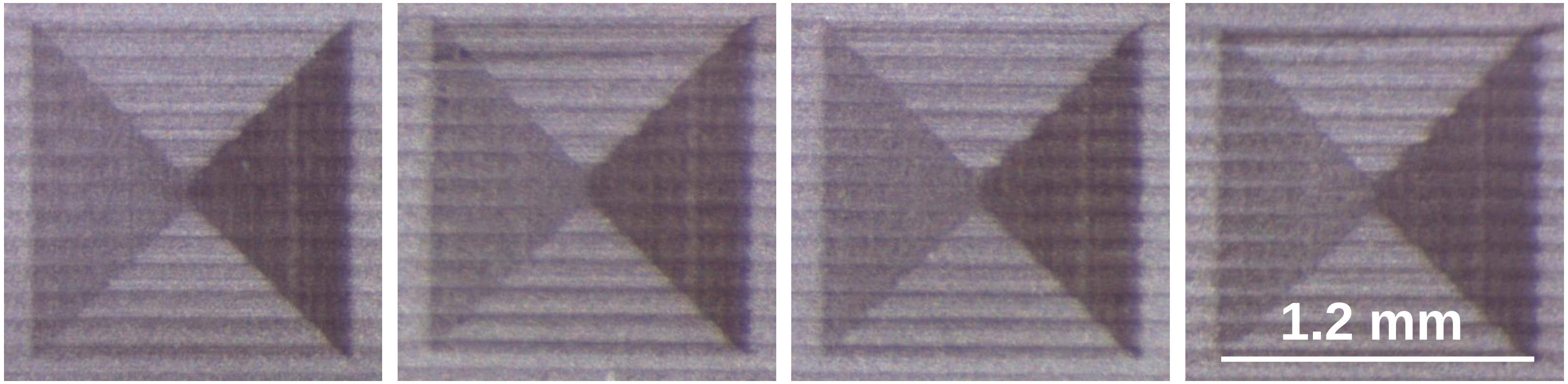
High-power processing results

- Pyramids with 204 layers, marked over 170mm in stainless steel
- Laser parameters:

P_{av}	=	42	W
v	=	95	m/s
f_{rep}	=	8.2	MHz

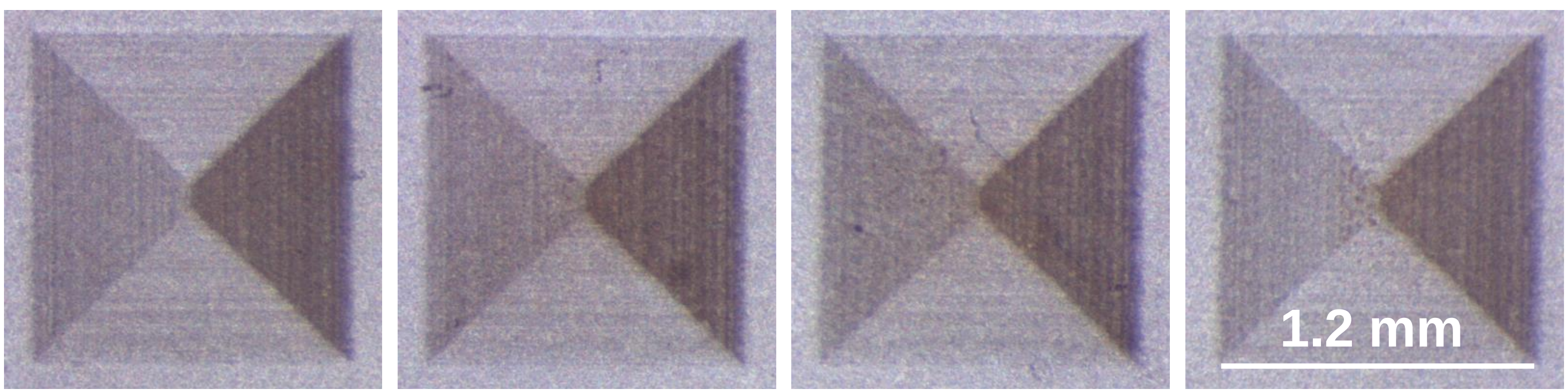
- No post-processing / cleaning
- No melt-formation



start 1/3 2/3 end

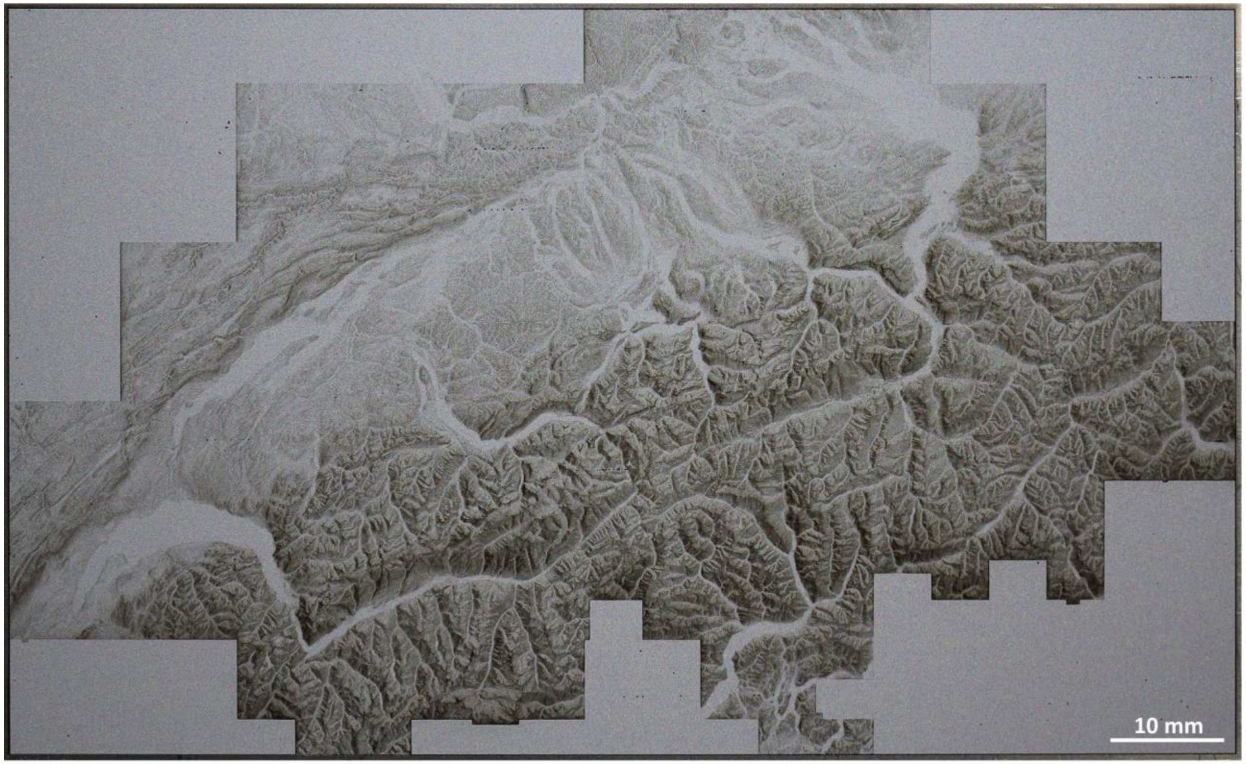
High-power processing results

- Pyramids with 204 layers, marked over 170mm in stainless steel
- Laser parameters:
  P_{av} = 42 W
  v = 95 m/s
  f_{rep} = 8.2 MHz
- No post-processing / cleaning
- Single-facet (maximum quality):



start | 1/3 | 2/3 | end

High-power processing results



- Topography of Switzerland in stainless steel, 2233 slices
- Laser parameters: P_{av} = 25.6 W

  v = 59.5 m/s

  f_{rep} = 4.1 MHz
- Strategy: averaging of pyramidal error
- No post-processing / cleaning

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Outlook

- Next-generation polygon-scanners will have active correction for all discussed errors implemented
- Scanning speed will be further increased (for lasers P_{av} > 100 W) while positioning-accuracy will be further improved
- Different line-length formats will be commercially available

Conclusion

1. Polygon line-scanners are an interesting option to «bring available power on the road»

2. Flexible laser systems with high repetition rates are key

3. For today's laser systems, v > 100 m/s is required for high-throughput, high-quality results

Acknowledgement

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