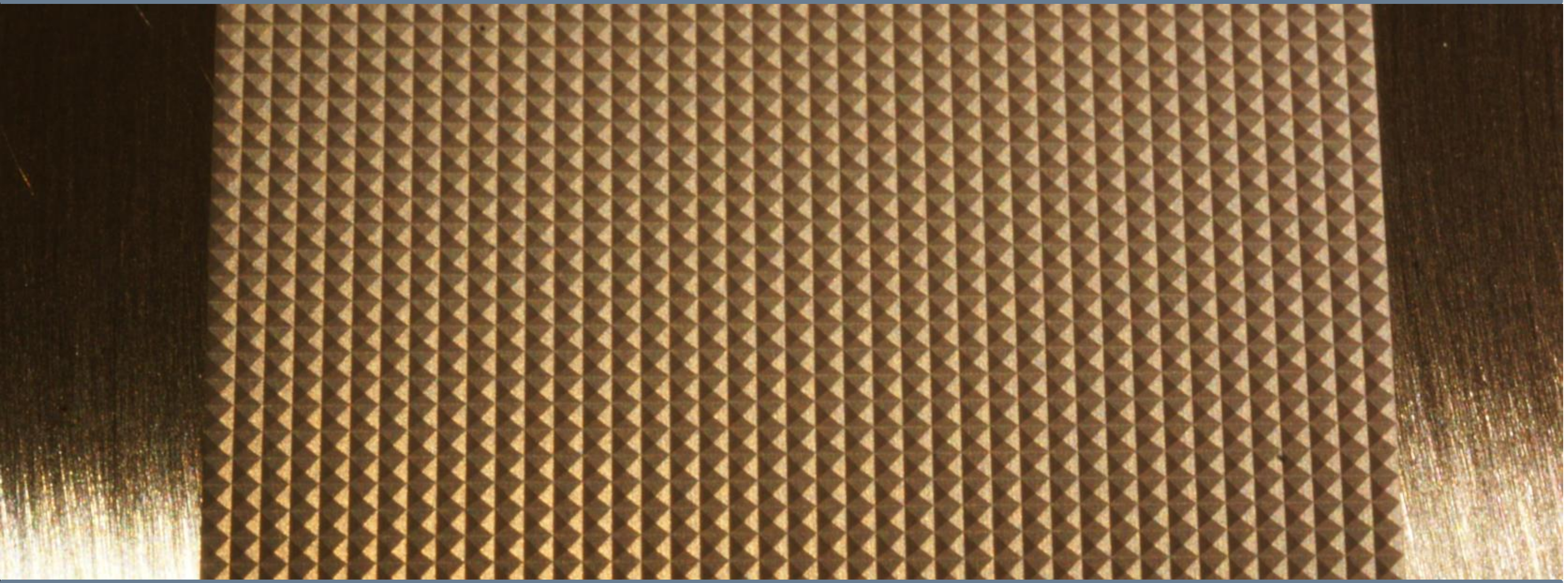
Berner Fachhochschule
Haute école spécialisée bernoise
Bern University of Applied Sciences



Applications of SLM in Laser Surface Engineering

B. Neuenschwander, T. Kramer, S. Remund

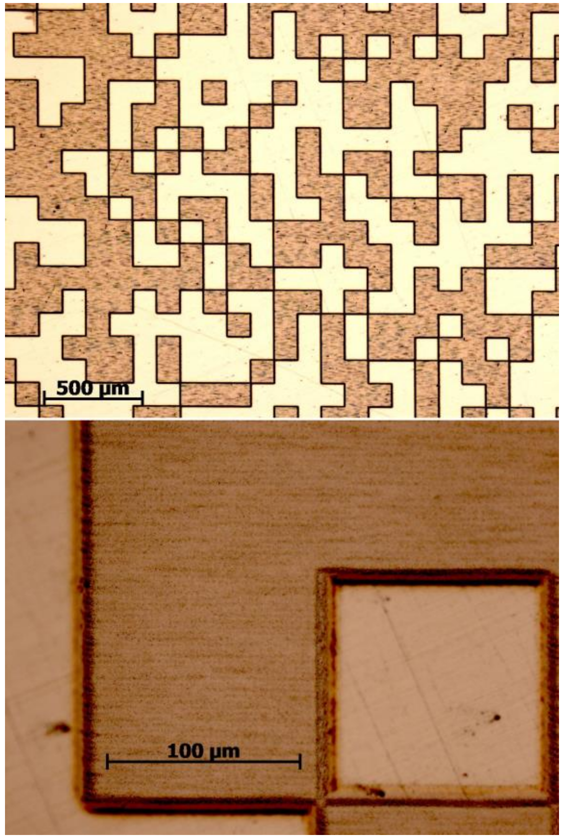
- Bern University of Applied Sciences / Institute for Applied Laser, Photonics and Surface Technologies

Outline

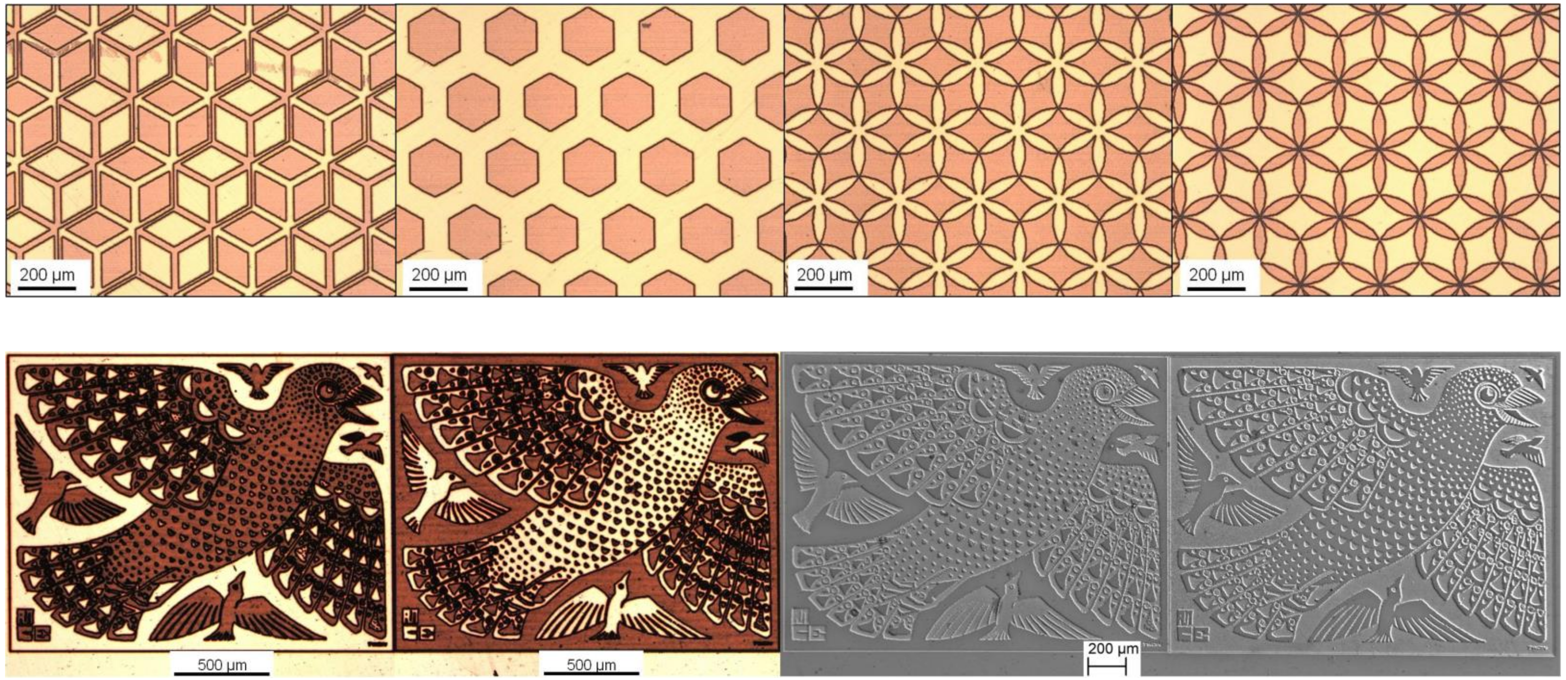
- Motivation
- Power Scaling
- SLM Applications
  - Multi-Spot Examples
  - Direct Beam Forming
- Limits
- Conclusions

Example: Precise 2D Structures in Copper

2D Barcode in Copper



2D Structures in Copper

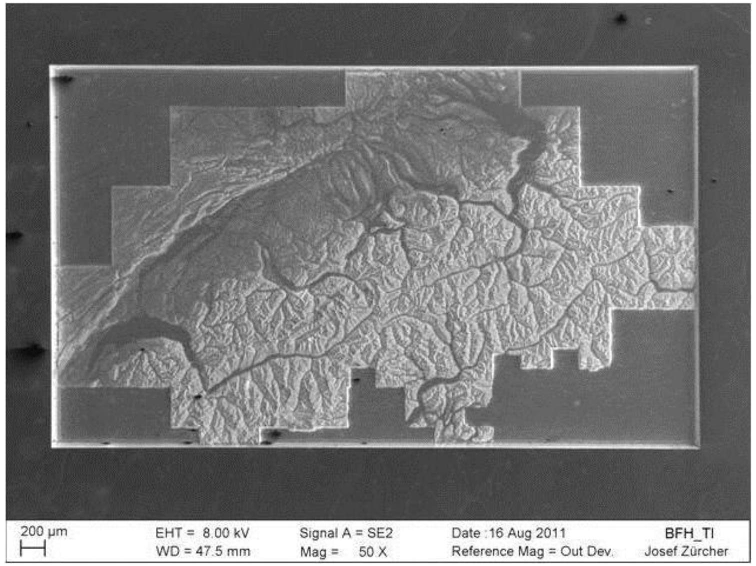


Example: Grayscale Bitmap as 3D-Relief in Copper

http://brettworks.com/2012/04/26/on-the-musicality-of-m-c-escher/

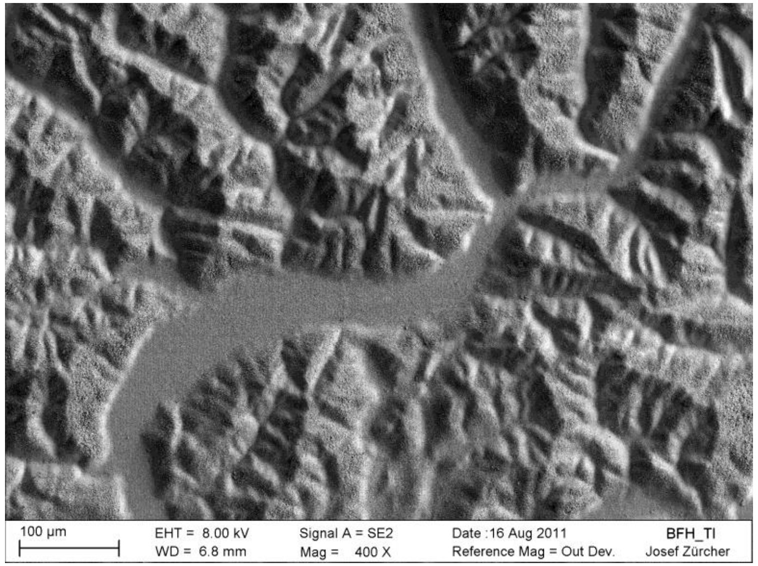
Example: Topography of Switzerland Machined in Copper

Topography in copper



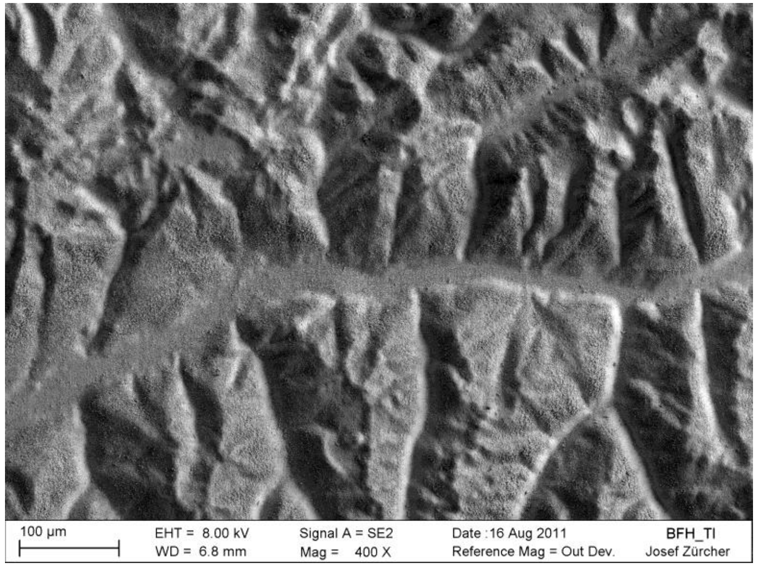
http://www.swisstopo.admin.ch/internet/swisstopo/de/home.html

Ticino



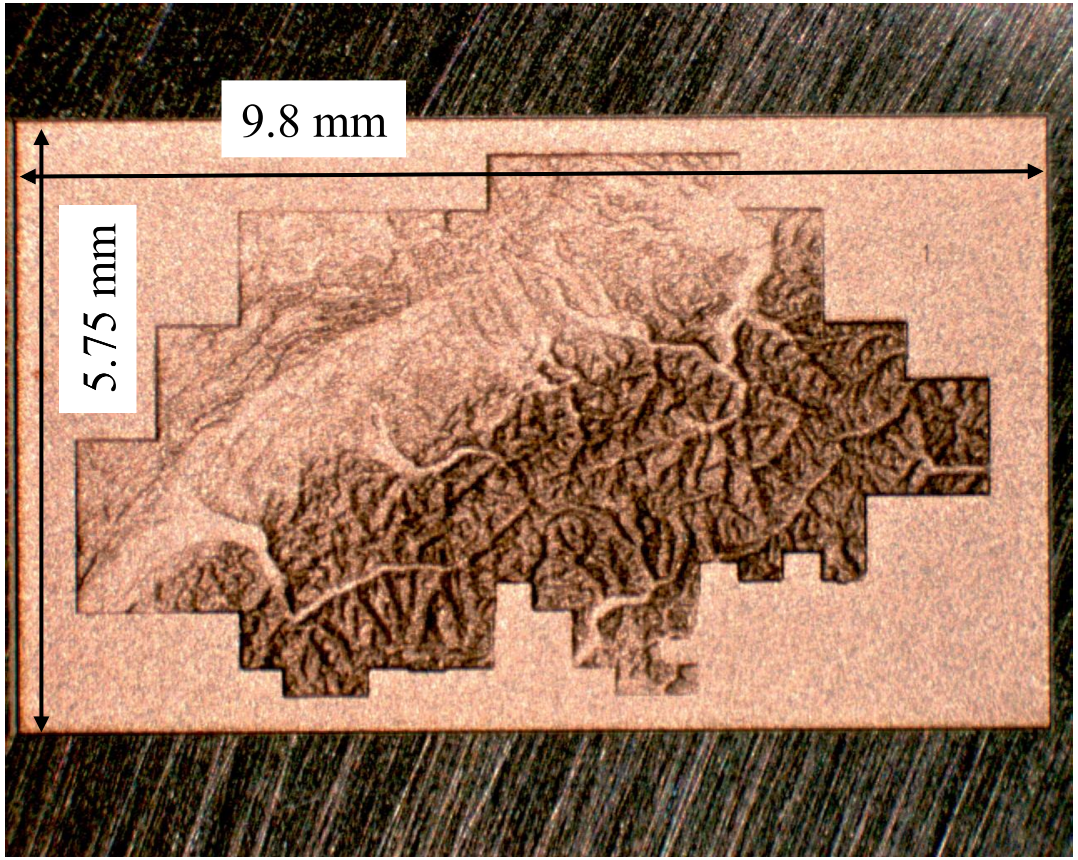
Tessin

Valais



Wallis

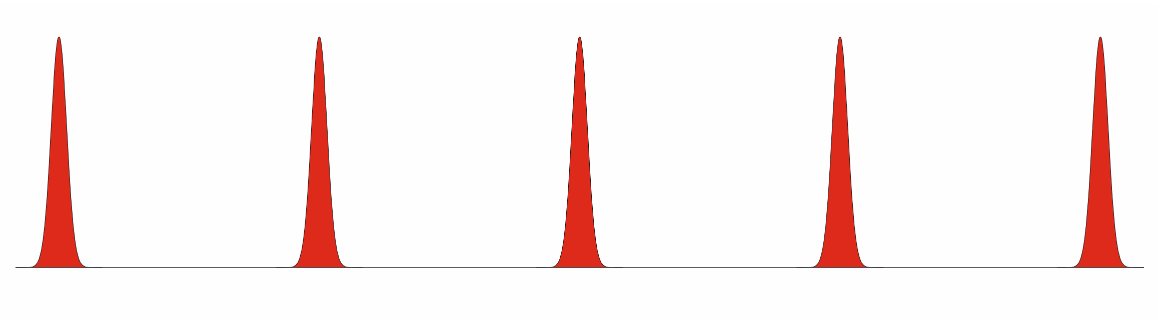
Throughput and Power Scaling



- Beside the machining quality especially the throughput and hence the removal rate $\Delta V/\Delta t$ is of huge importance
- The throughput finally scales with the average power P_{av}

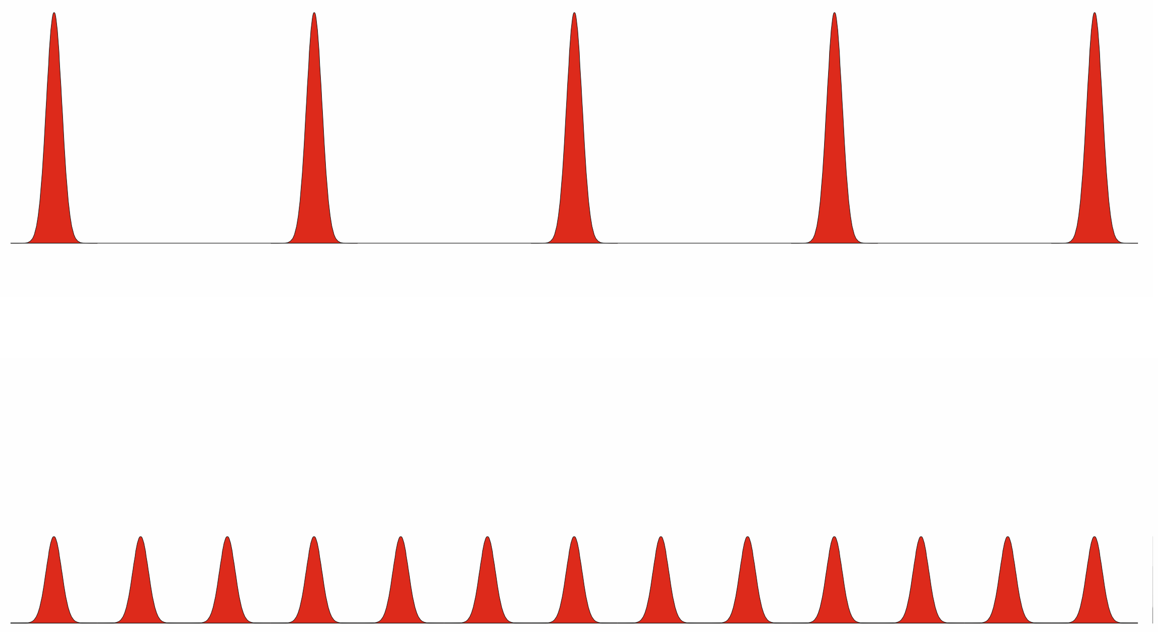
- Linear scaling?
  - $P_{av} = 4\,W,\ \frac{\Delta V}{\Delta t} = 0.5\,\frac{mm^3}{min},\ \Delta t = 70\,min$
  - $P_{av} = 40\,W,\ \frac{\Delta V}{\Delta t} = 5.0\,\frac{mm^3}{min},\ \Delta t = 7\,min$?

Increasing Average Power



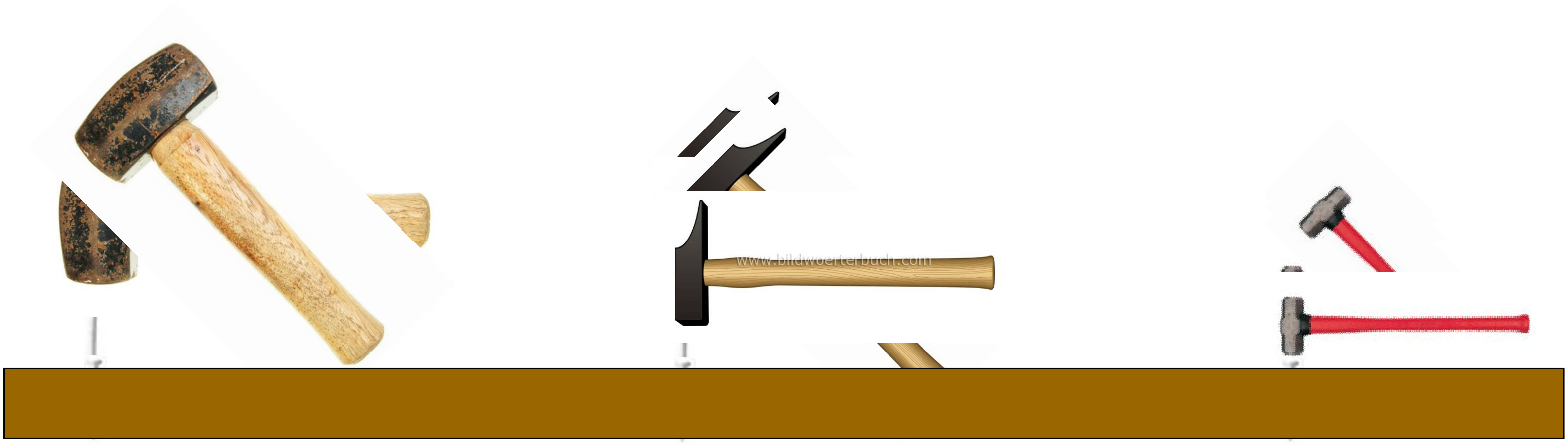
- $P_{av} = f \cdot E_P$
  - f: Repetition rate
  - E_p: Pulse energy

Increasing Average Power



- $P_{av} = f \cdot E_P$
  - f: Repetition rate
  - E_p: Pulse energy
- Both possible?
- Differences?

Hammer and Nail

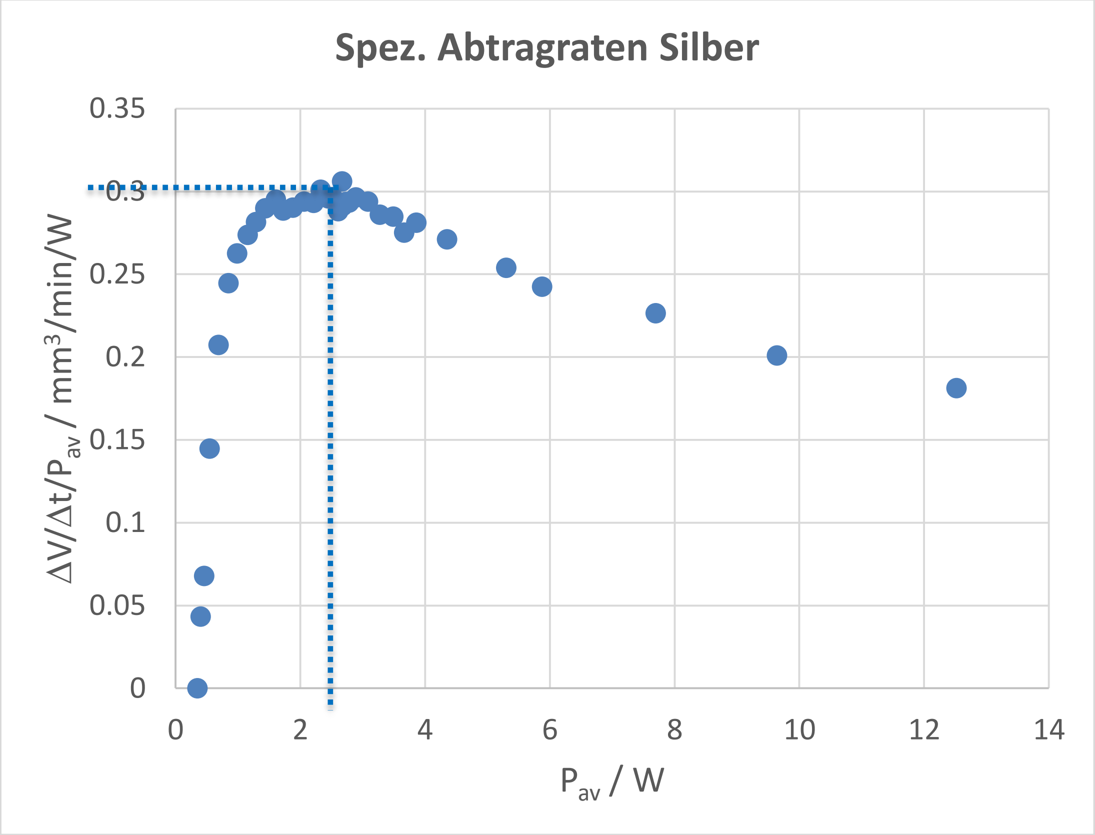


Example: Silver

- Machining of 2x2 mm squares at different average powers (E_P)
- Nonlinear increase of the removal rate
- The specific removal rate (efficiency) is given by

$$\frac{\Delta V}{\Delta t \cdot P_{av}}$$

- and shows a maximum value at a certain average power i.e. pulse energy

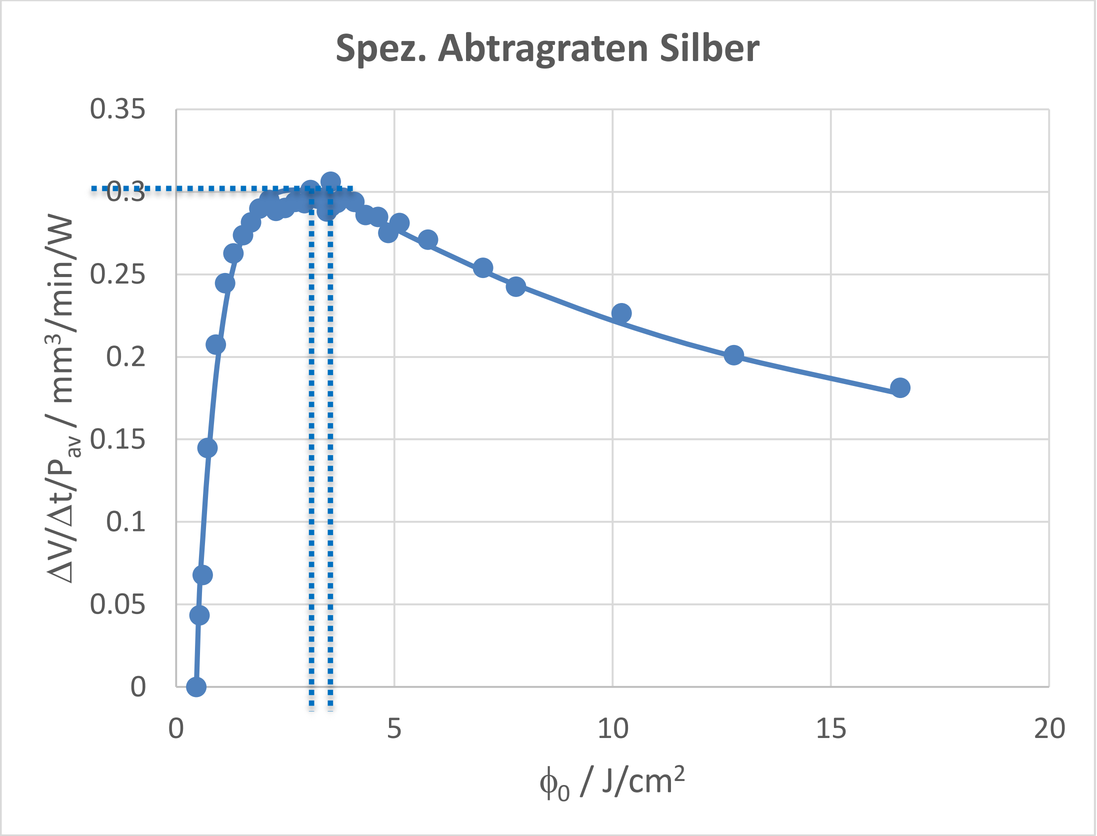


Example: Silver

- The spec. removal rate shows a maximum value at a certain average power i.e. pulse energy or fluence (pulse energy per area)
- For a Gaussian beam follows:

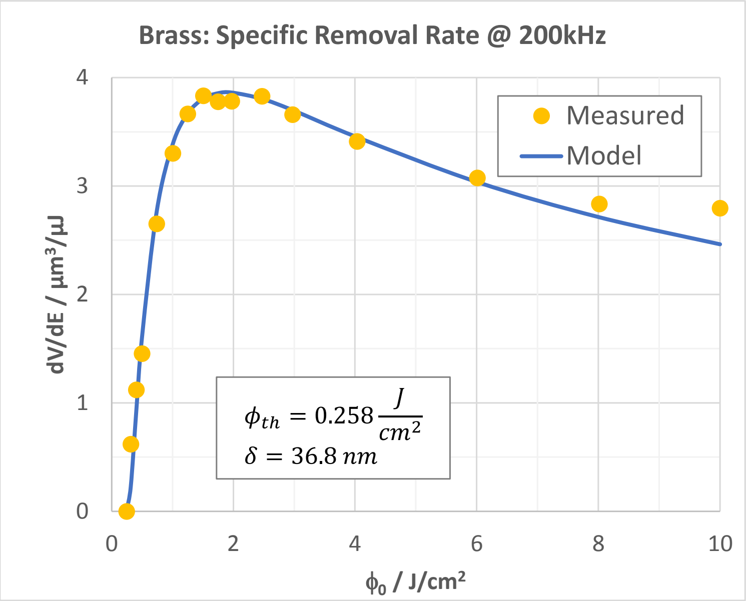
$$\frac{\dot{V}}{P_{av}} = \frac{1}{2} \cdot \frac{\delta}{\phi_0} \cdot \ln^2\left(\frac{\phi_0}{\phi_{th}}\right)$$

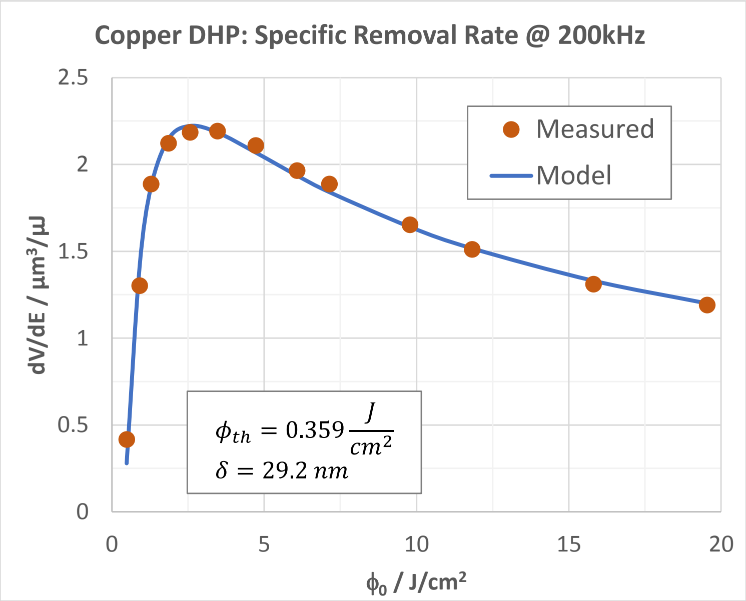
  - ϕ_{th}: Threshold fluence
  - δ : Energy penetration depth
  - ϕ_0: Peak fluence

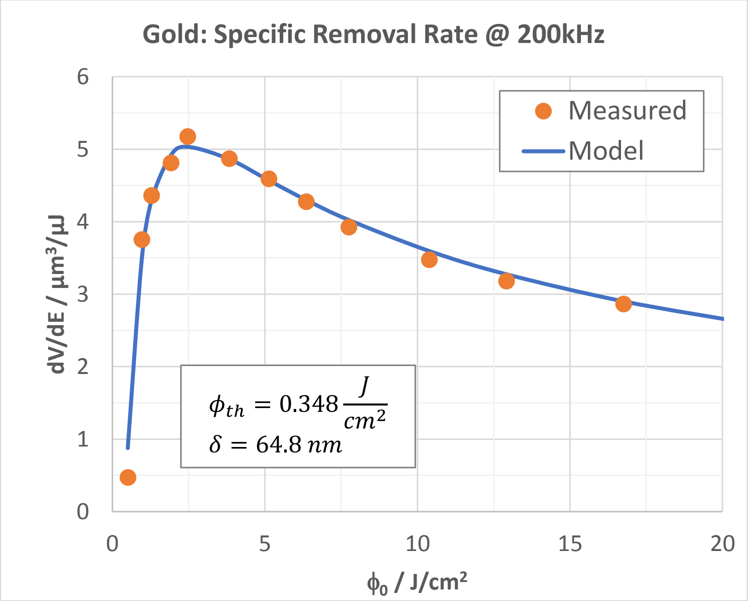


Brass, Copper and Gold

- Brass: $\Delta\tau$ = 10 ps, w_0 = 16 µm
- Copper: $\Delta\tau$ = 10 ps, w_0 = 16 µm
- Gold: $\Delta\tau$ = 10 ps, w_0 = 16 µm





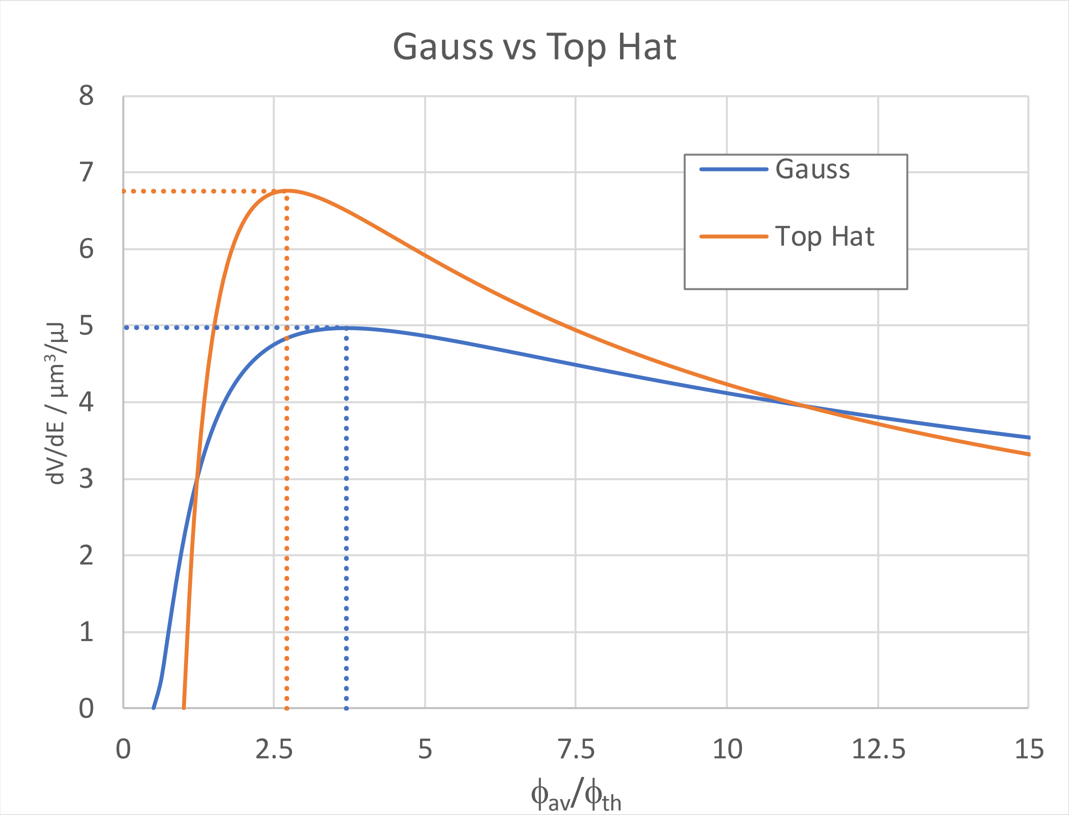


$$\left.\frac{\dot{V}}{P_{av}}\right|_{max} = 0.232\ \frac{mm^3}{min \cdot W} = 3.86\ \frac{\mu m^3}{\mu J}$$

$$\left.\frac{\dot{V}}{P_{av}}\right|_{max} = 0.133\ \frac{mm^3}{min \cdot W} = 2.22\ \frac{\mu m^3}{\mu J}$$

$$\left.\frac{\dot{V}}{P_{av}}\right|_{max} = 0.302\ \frac{mm^3}{min \cdot W} = 5.03\ \frac{\mu m^3}{\mu J}$$

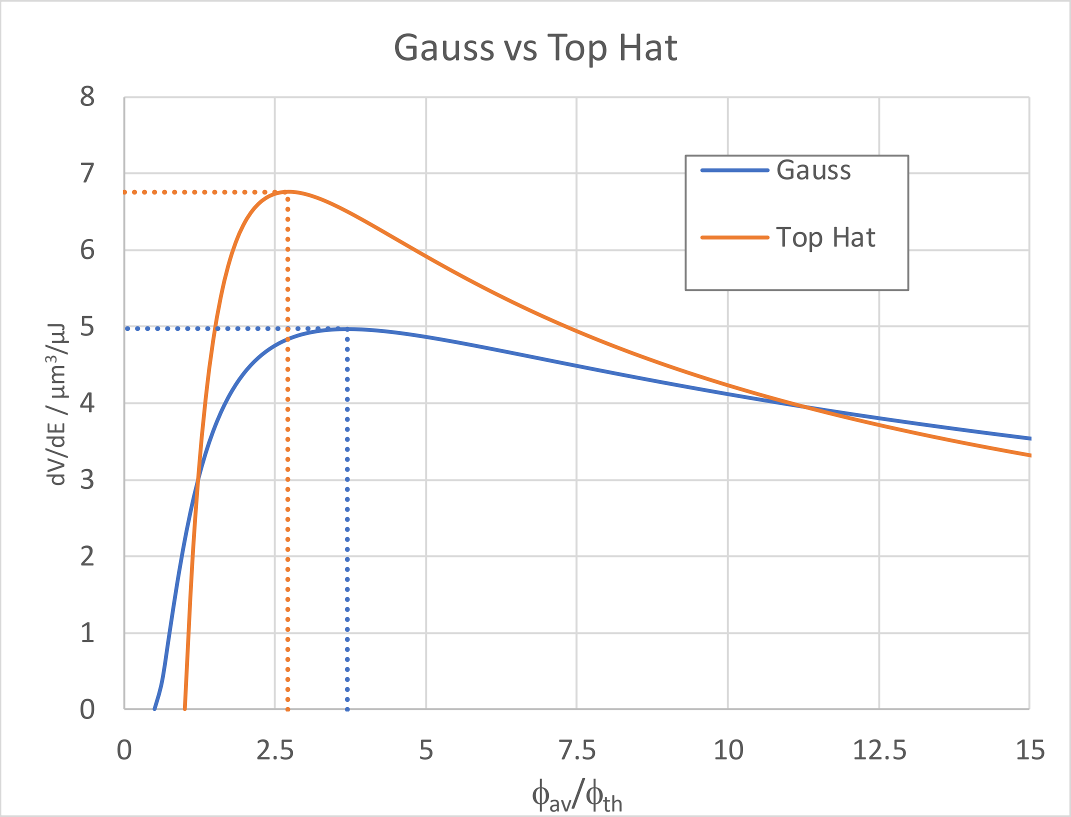
Gauss vs Top Hat Intensity distribution



- Gauss:
  - $\frac{\dot{V}}{P_{av}} = \frac{dV}{dE} = \frac{1}{4} \cdot \frac{\delta}{\phi_{av}} \cdot ln^2\left(\frac{2\phi_{av}}{\phi_{th}}\right)$
  - $\phi_{av,opt} = \frac{e^2}{2} \cdot \phi_{th}, \quad \left.\frac{dV}{dE}\right|_{max} = \frac{2}{e^2} \cdot \frac{\delta}{\phi_{th}}$
- Top Hat:
  - $\frac{\dot{V}}{P_{av}} = \frac{dV}{dE} = \frac{\delta}{\phi_{av}} \cdot ln\left(\frac{\phi_{av}}{\phi_{th}}\right)$
  - $\phi_{av,opt} = e \cdot \phi_{th}, \quad \left.\frac{dV}{dE}\right|_{max} = \frac{1}{e} \cdot \frac{\delta}{\phi_{th}}$

- Top Hat is more efficient

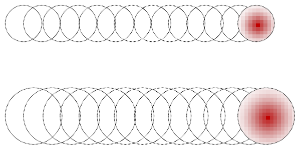
Efficient machining



- Top Hat is more efficient
- Optimum fluences are near the threshold fluence
  - Small spots needs only moderate pulse energies and therefore high repetition rates and fast scanning speeds
  - High pulse energies demand large spots or large area machined by one pulse

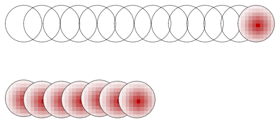
Strategies for High Pulse Energies

- Increase spot size

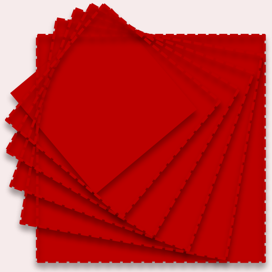


  - for micromachining?

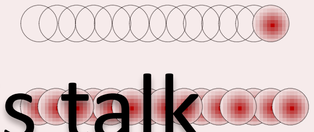
- Multi-spots: Temporal, Bursts:



- Forming the spot

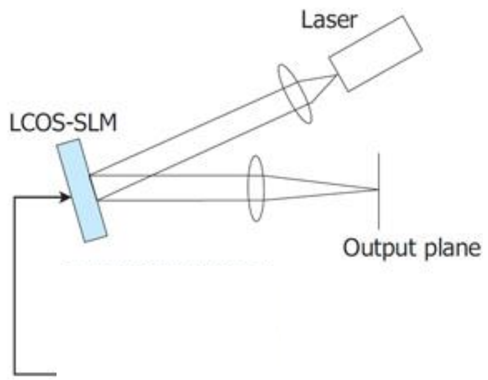


- Multi-spots: Spatial



Topic if this talk

Typical SLM Set-Up

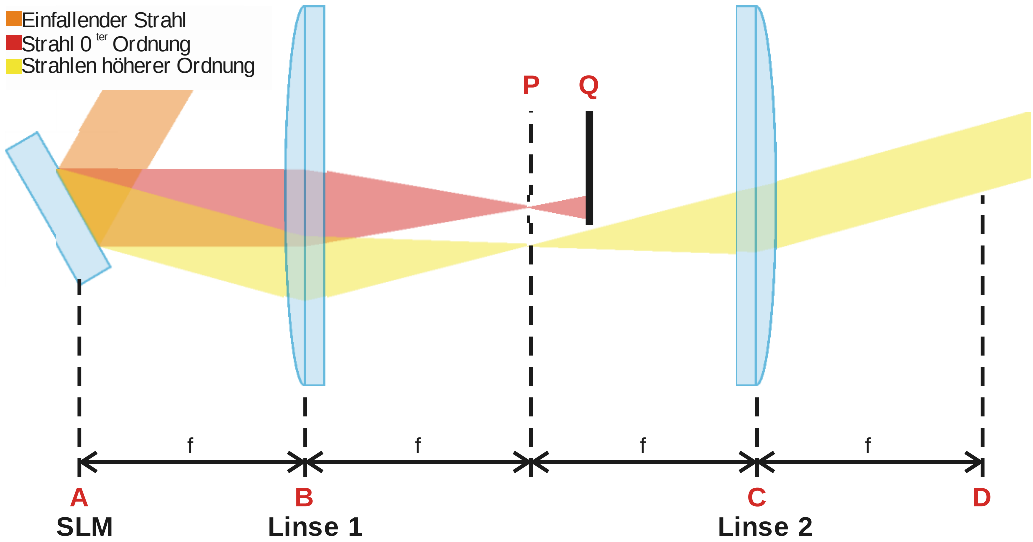


Picture from http://www.hamamatsu.com/jp/en/product/alpha/L/4015/index.html

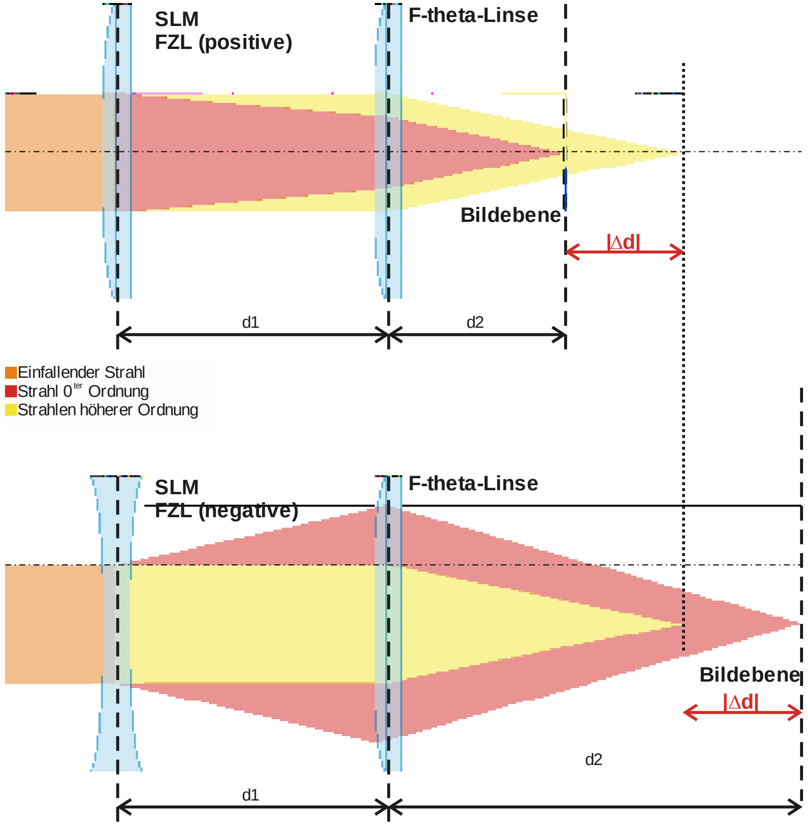
- Additional phase is added to a collimated (Gaussian) beam
- Specific patterns can be produced in the output plane
- SLM is a phase-only device
- Grating structure leads to a 0^{th} order
- Some multi-spot patterns may use the 0^{th} order

Surpression of 0th Order

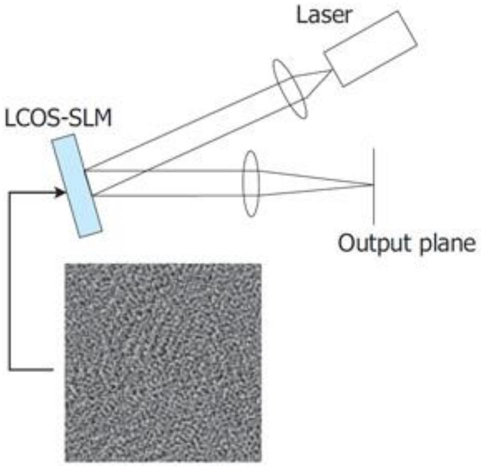
Working in 1st order

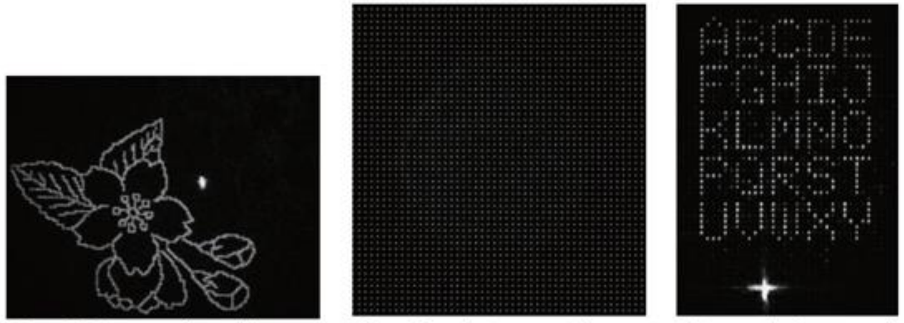


Add fresnel zone lens



Typical SLM Set-Up





Clear CGH reproduced image (+1st order light) | 50 × 50 point generation with 0th order suppressed | Text reproduction example (+1st order light)

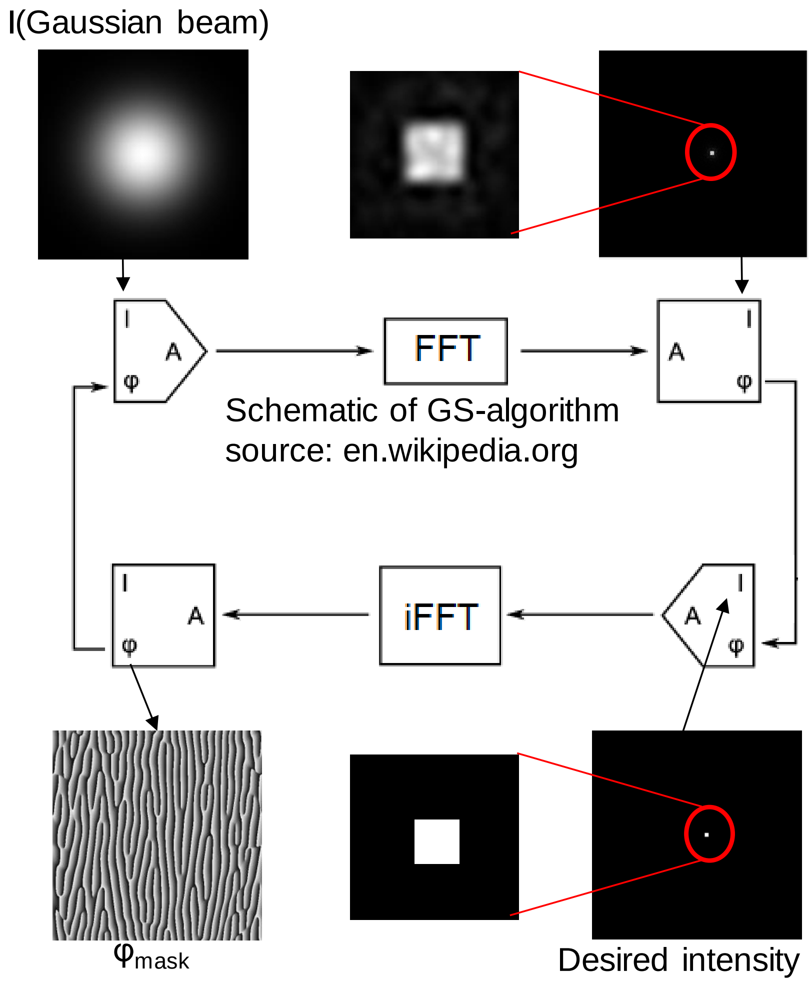
- How to generate the phase information for a specific pattern?
- E.g. by an iterative Fourier transform algorithm

Picture from http://www.hamamatsu.com/jp/en/product/alpha/L/4015/index.html

Calculation of Phase Mask

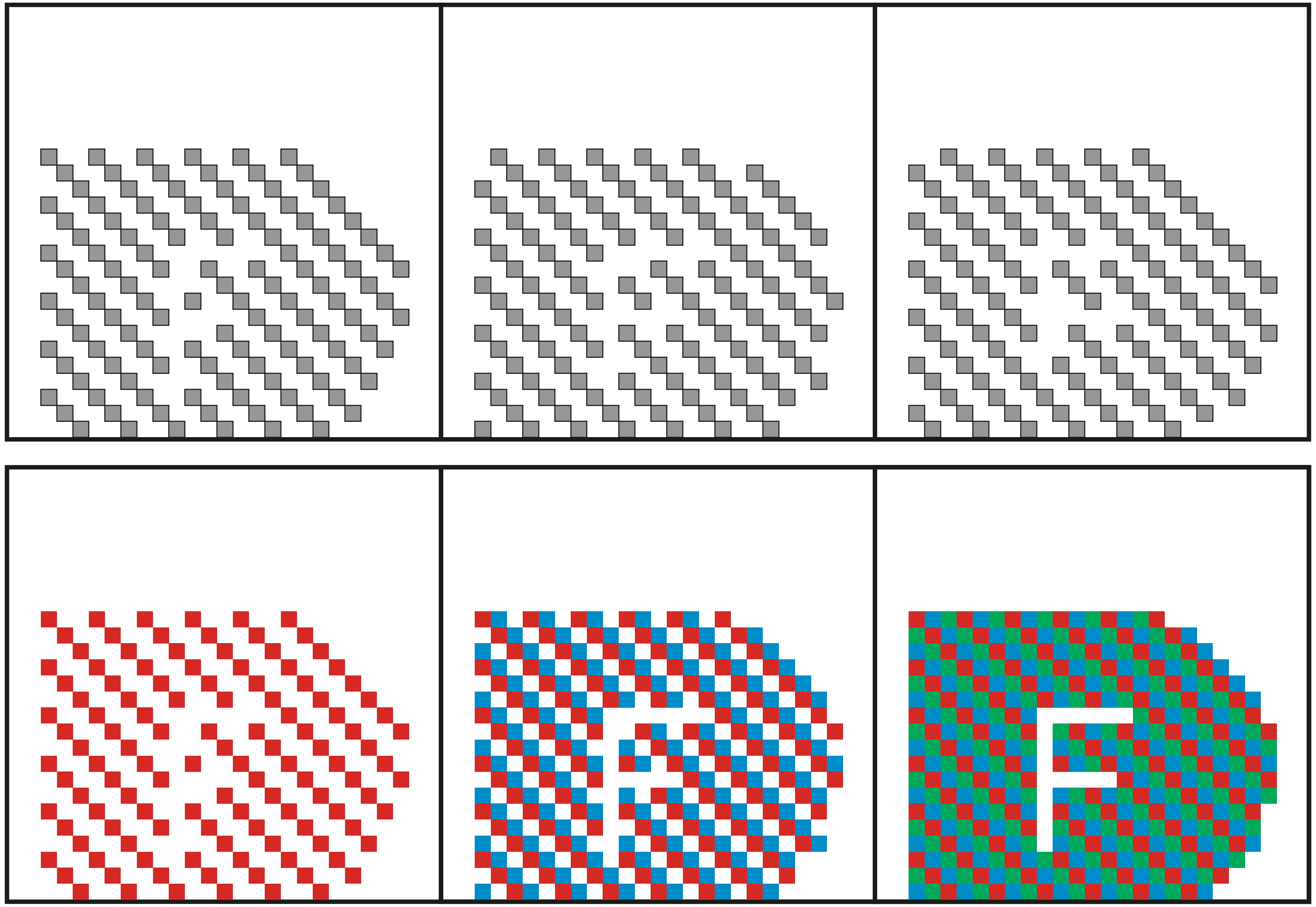
Iterative Fourier transform algorithm:

- Initialize in SLM plane
  Gaussian beam intensity initial
  random phase: $0 \leq \varphi < 2\pi$
  - FFT for calculating intensity in the focal plane
  - Replacement of the amplitude, keeping the phase
  - Inverse FFT for calculating the phase distribution φ_{mask} in the SLM plane
  - Replacement of the amplitude by incident beam



Picture from Prof. Michael Schmidt University of Erlangen

Multi-Spot Example 1



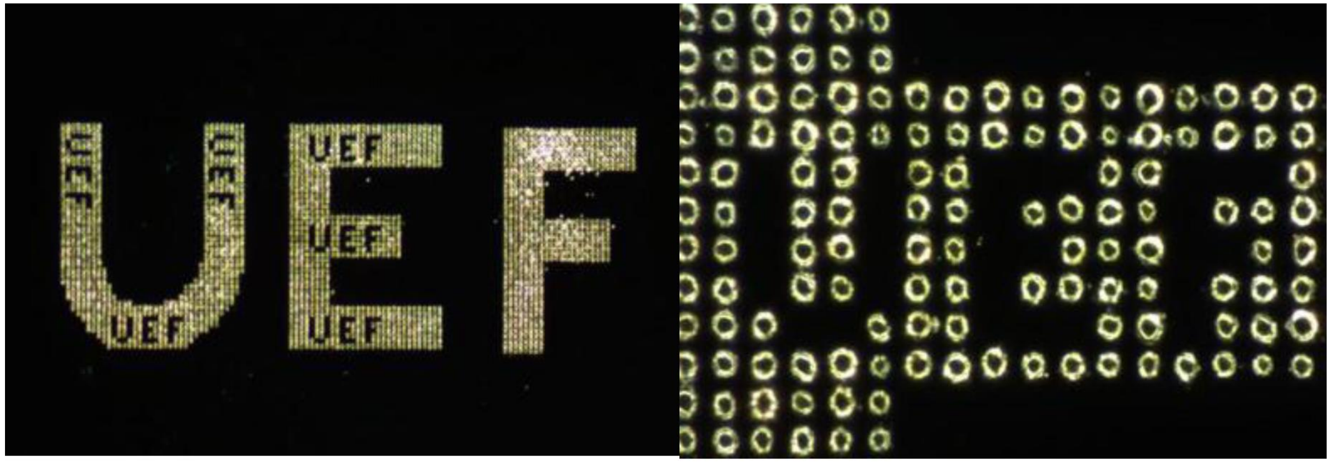
- Division of a pattern in sup-patterns
- Machining of these sub-patterns in a sequence

Multi-Spot Example 1

- Division of a pattern in sup-patterns
- Machining of these sub-patterns in a sequence

K.Päiväsaari, M. Silvennoinen, J. Kaakkunen and P.i Vahimaa, “Femtosecond laser processing and spatial light modulator “, SPIE 8967-14 (2014)

Multi-Spot Example 2



- Blank out single spots in a regular pattern of nxn spots
- Move target and apply different patterns

M. Silvennoinen, J. Kaakkunen, K. Paivasaari, P. Vahimaa, ” Parallel microstructuring using femtosecond laser and spatial light modulator”, Phys. Proc. 41, 693 (2013)

Multi-Spot Example 2

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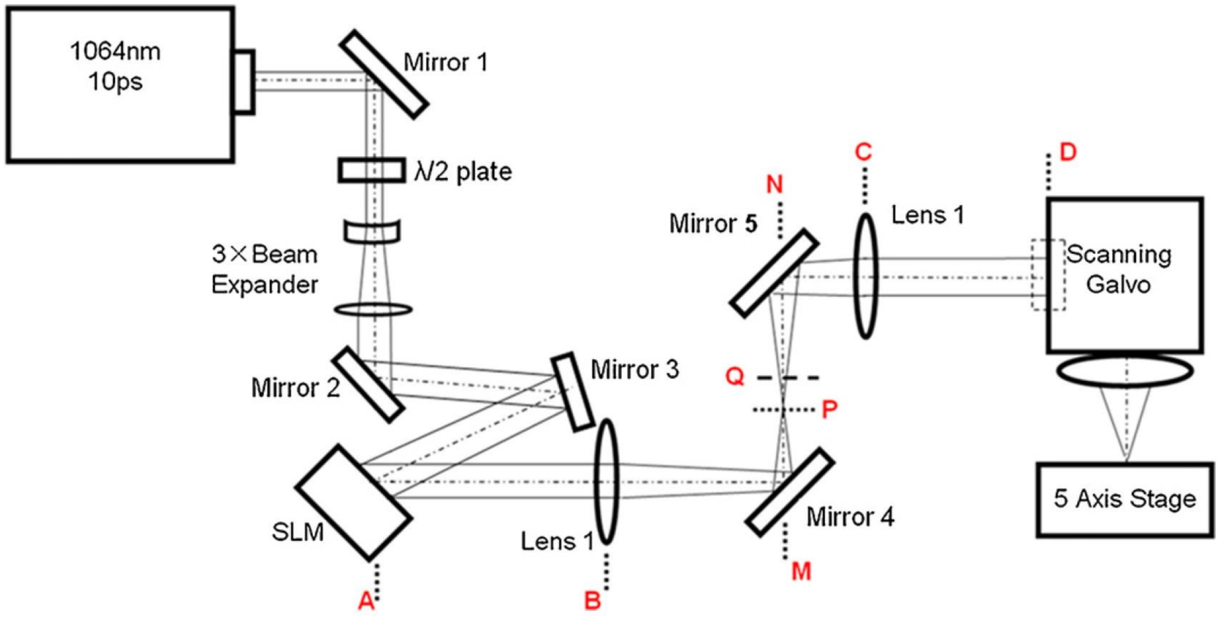
K.Päiväsaari, M. Silvennoinen, J. Kaakkunen and P.i Vahimaa, "Femtosecond laser processing and spatial light modulator ", SPIE 8967-14 (2014)

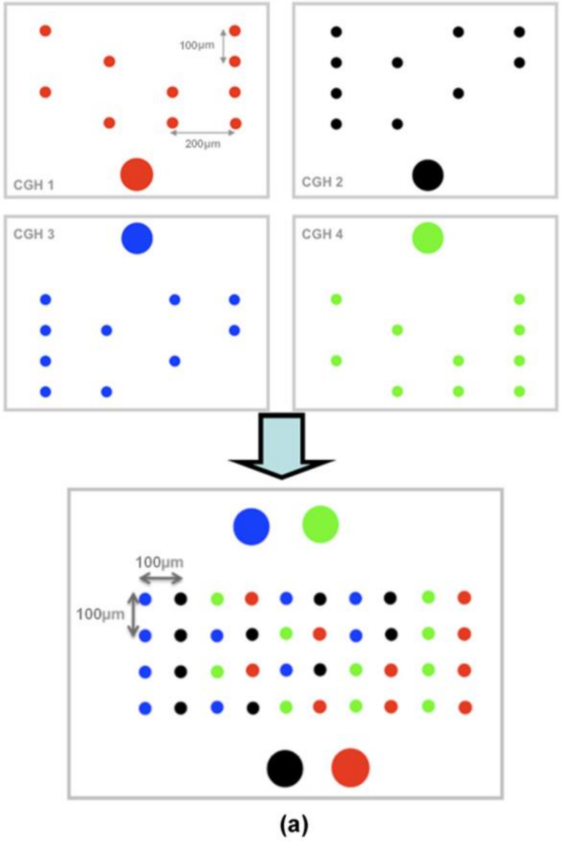
Multi-Spot Example 3: Cobination with Galvo Scanner

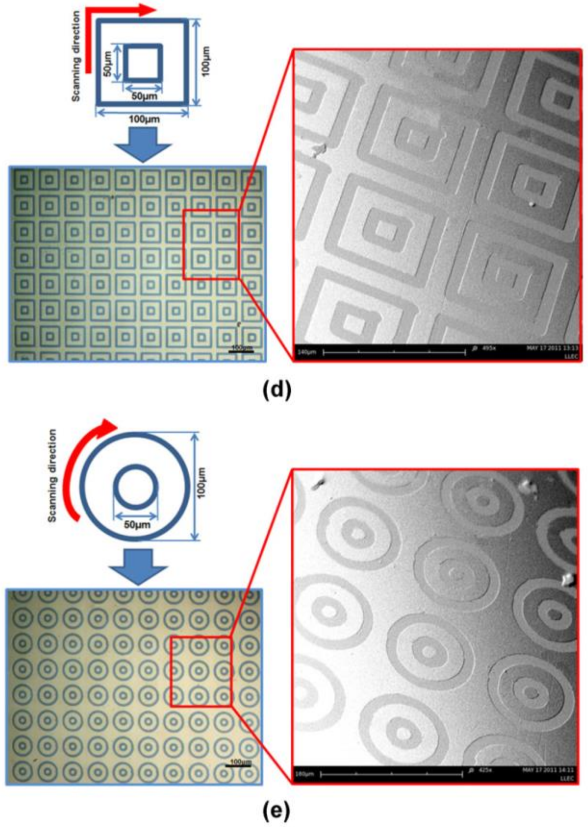


- Combination of SLM with Galvo Scanner

Z. Kuang, W. Perrie, D. Liu, P. Fitzsimons, S. P. Edwardson, E. Fearon, G. Dearden, K. G. Watkins, Appl. Surf. Sci., 258, 7601 (2012)

Multi-Spot Example 3: Combination with Galvo Scanner

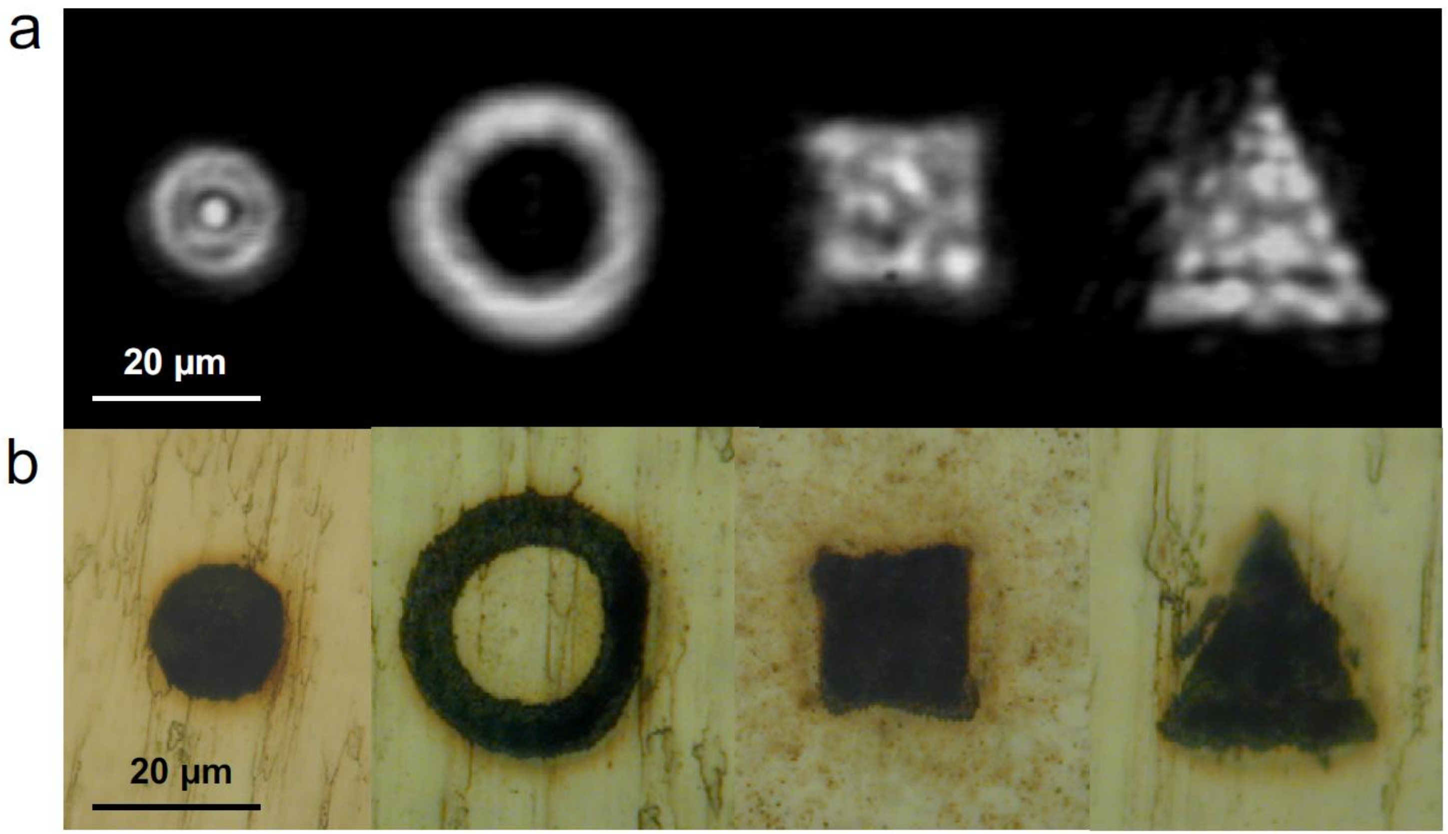




- Combination of SLM with Galvo Scanner
- Division in sub-patterns
- Machining of regular structures in ITO film

Z. Kuang, W. Perrie, D. Liu, P. Fitzsimons, S. P. Edwardson, E. Fearon, G. Dearden, K. G. Watkins, Appl. Surf. Sci., 258, 7601 (2012)

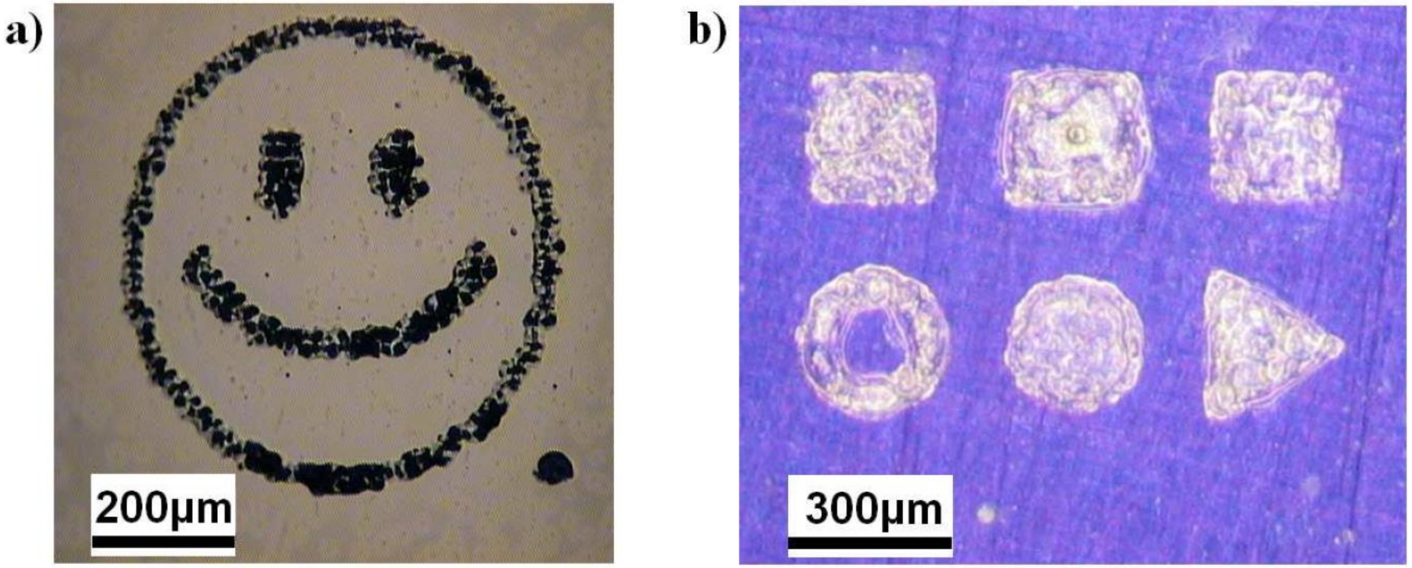
Beam Forming Example 1:



- Direct generation of a specific form by IFA
- Directly machined into stainless steel (130fs, 100kHz, 50’000 pulses, 0.2 J/cm^2)

N. Sannera, N. Huota,, E. Audouarda, C. Laratb, J.-P. Huignard, Opt. and Laser Eng., 45 (2007), 737

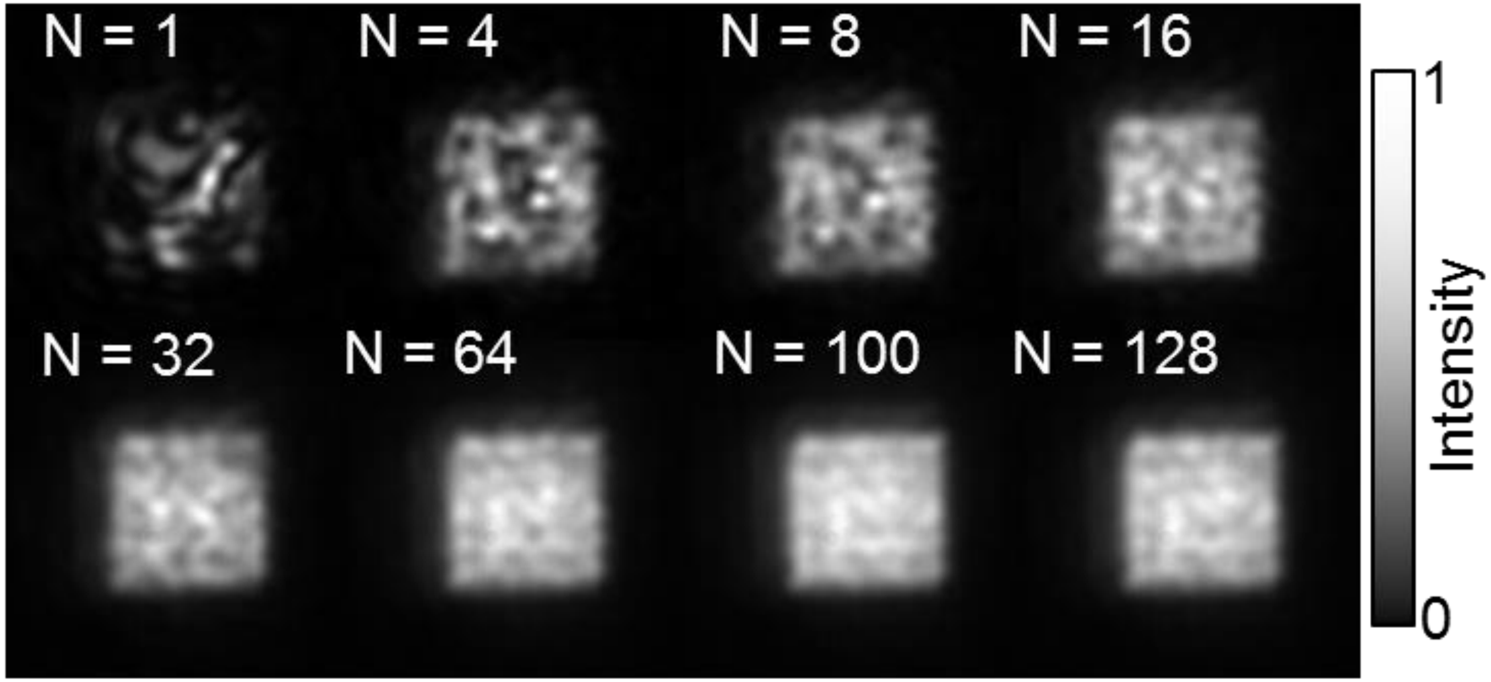
Beam Forming Example 2:



- Direct generation of a specific form by IFA
- Directly machined into stainless steel (65ns, 30kHz, 532nm, 14.7W, 3.2ms)
- Speckles observed in the patterns due to phase only modulation by the SLM

R. J. Beck, J. P. Parry, W. N. MacPherson, A. Waddie, N. J. Weston, J. D. Shephard, D. P. Hand, Opt. Expr., 18 (2010), 17059

Beam Forming Example 3: Speckle Reduction

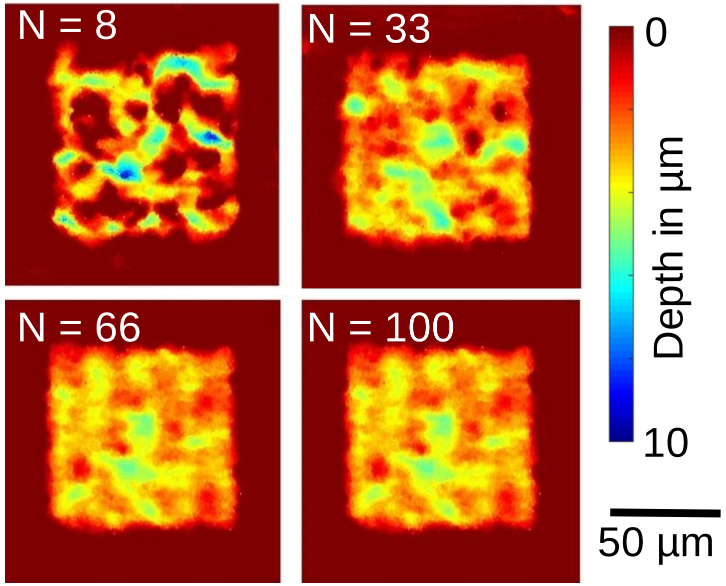


T. Häfner, J. Heberle, D. Holder, M. Schmidt, J. of Laser Appl., 29 (2017), 022205

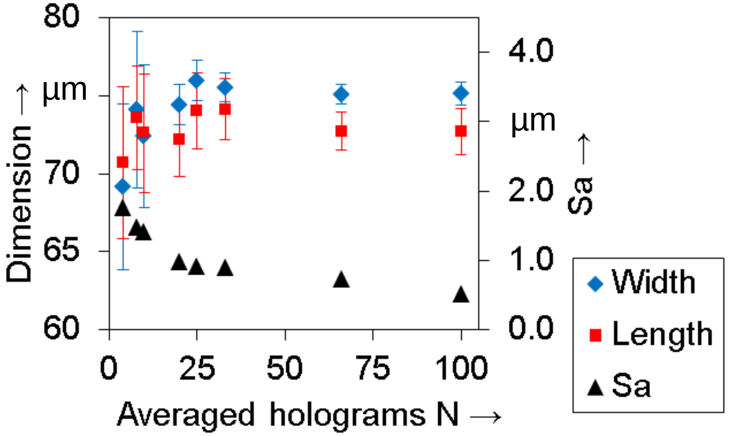
Time averaging

- Calculate several holograms with different random phases at start
- Play these holograms in a sequence on the SLM
- Significant speckle reduction by averaging
- N>70 is enough

Beam Forming Example 3: Speckle Reduction



Machined in steel 1.2379

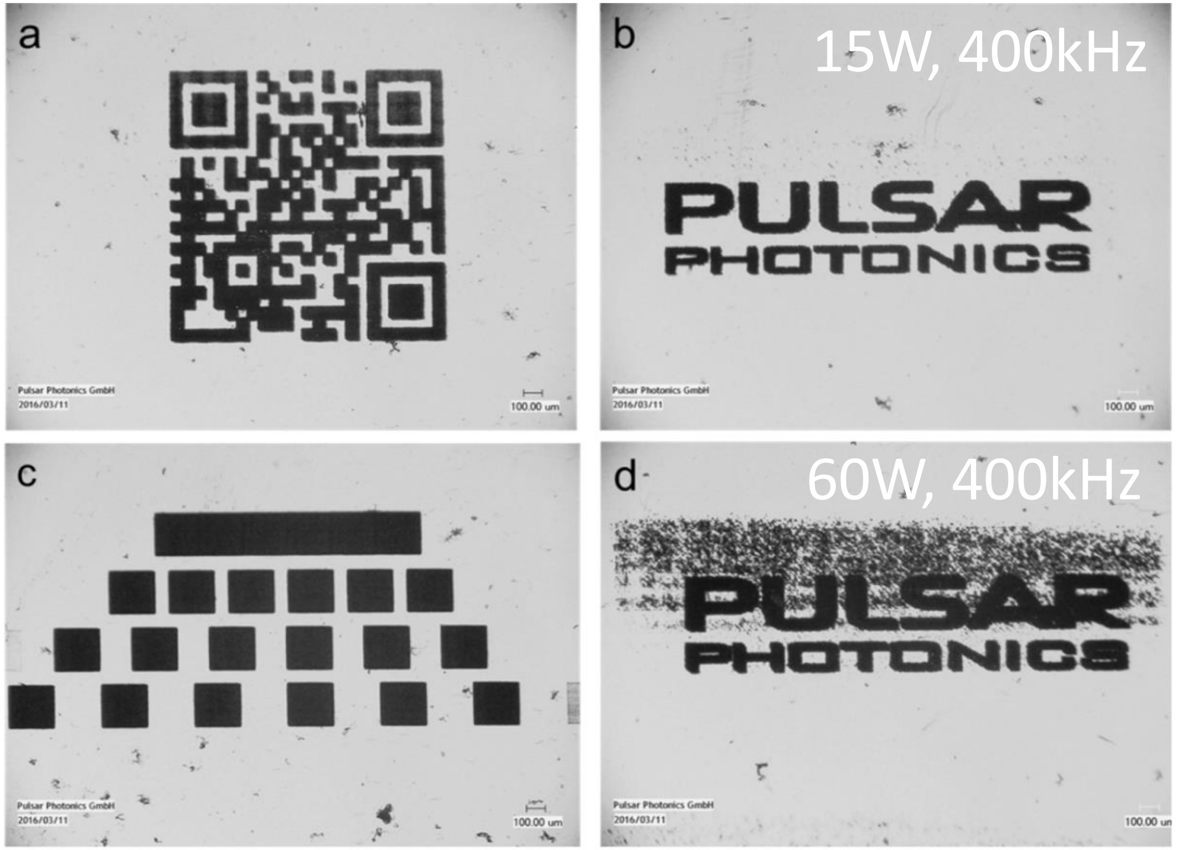


T. Häfner, J. Heberle, D. Holder, M. Schmidt, J. of Laser Appl., 29 (2017), 022205

- Roughness decreases with increasing N
- Fluctuation of lateral structure dimensions stagnate at N > 33

- Averaging of multiple holograms not applicable for homogeneous thin layer ablation with low number of laser pulses

Beam Forming Example 4: Industrial realisation



T. Klerksa, S. Eifel, 9th International Conference on Photonic Technologies LANE 2016, Industrial Paper

Typical System Performance

- Linear and nonlinear laser induced damage threshold (NIR):
  - >0.50 J/cm² (50 GW/cm²)(10 ps)
  - >100 W/cm² (cw)
- Limited by evaporation of the LC

- Switching rate of LCoS display limited by liquid crystals
- Switching rate max. 250 Hz
- (Quasi) Static patterns applicable for cw and pulsed lasers

Conclusion

- Efficient laser micromachining uses fluences near the threshold fluence
- Power scaling need either high repetition rates or large areas machined by one pulse
- Spatial light modulators offer the possibility to dynamically generate such large areas
  - Multi-spot strategies
  - Direct beam forming
- Speckles occur for direct beam forming, reduced by averaging of a hologram sequence
- First industrial products already available
- System performance has to be improved for many applications

Thank you for your Attention