Plasmons in Metallic Nanostructures: Excitation, Propagation and Detection

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University of Konstanz

Outline

- Introduction

- Localized plasmon modes in gold nanoparticles
  imaged by
  - local ablation of a substrate
  - local melting of the structures
  - two-photon photopolymerization

- Propagating plasmon modes in thin mesoscopic gold stripes
  on Silicon membranes, imaged by
  - plasmon-phonon conversion
  - plasmon-photon conversion

- Conclusions

Optical Antenna

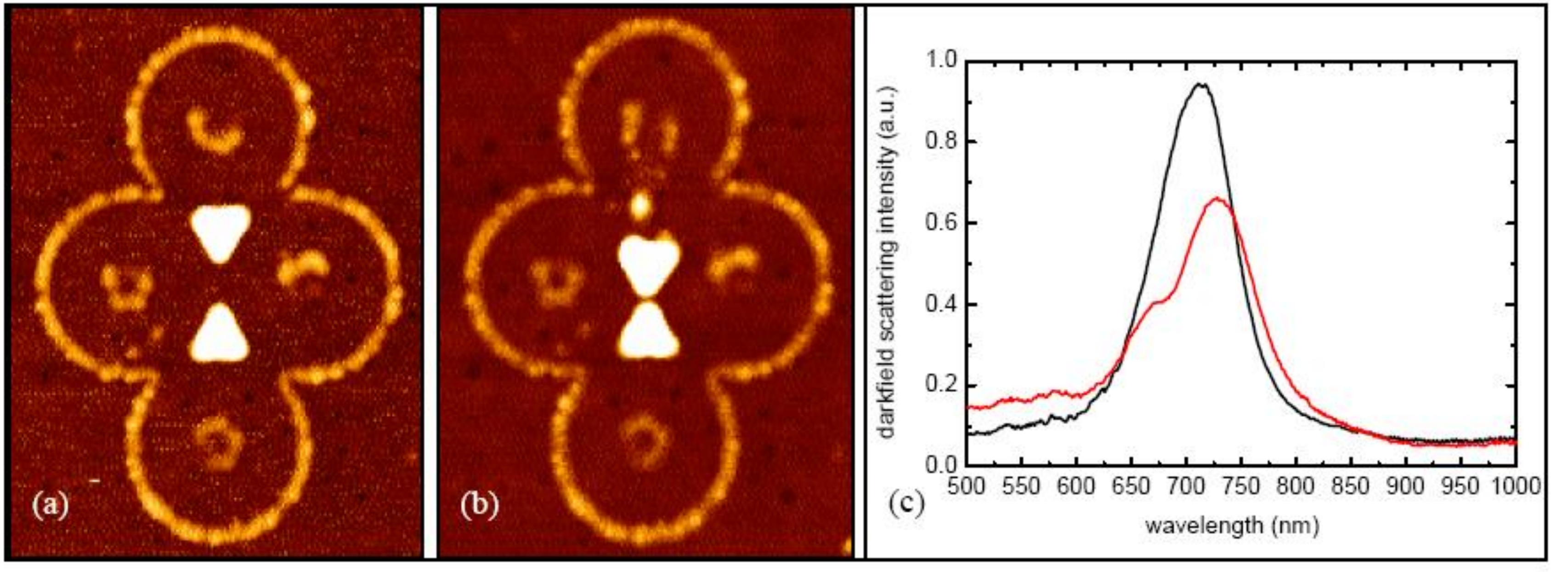


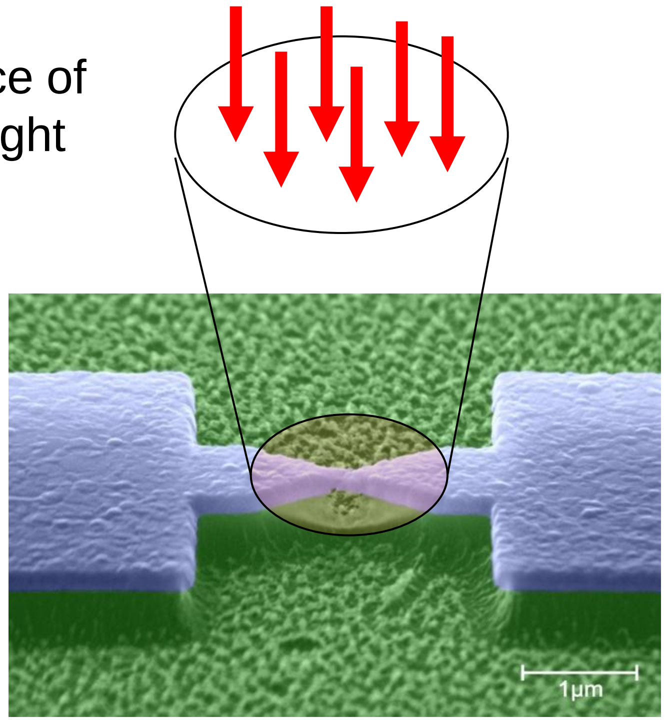
Fig. 1. Atomic force microscope images (a and b) and dark field scattering spectra (c) of a single gold bowtie optical nanoantenna with feedgap of 35 nm (black line) and 5 nm (red line).

triangle edge length 128nm, thickness 32nm

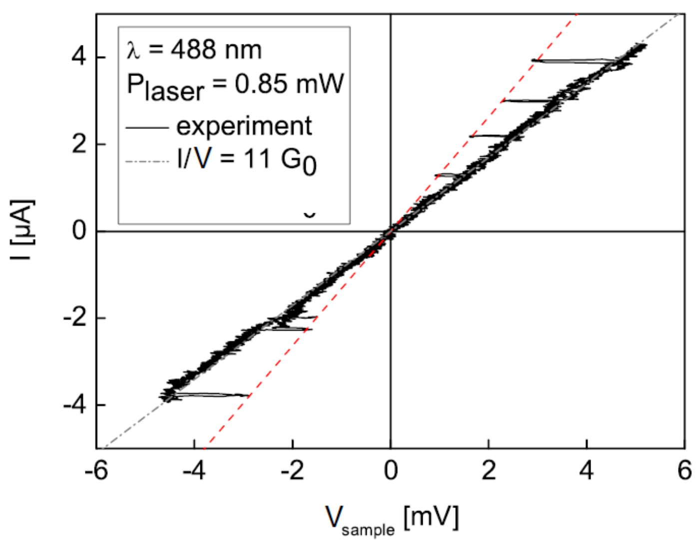
Merlein et al., Nature Photonics **2**, 230 (2008)

Electronic Transport Through Atomic-Size Contacts

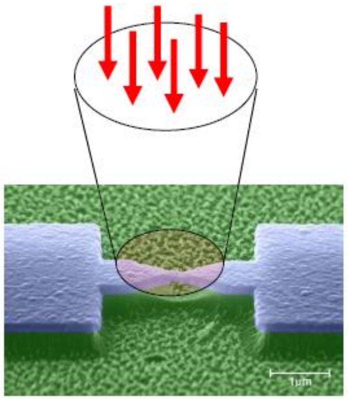
Influence of laser light



$G_0 = 2e^2/h \approx 1/12k\Omega$



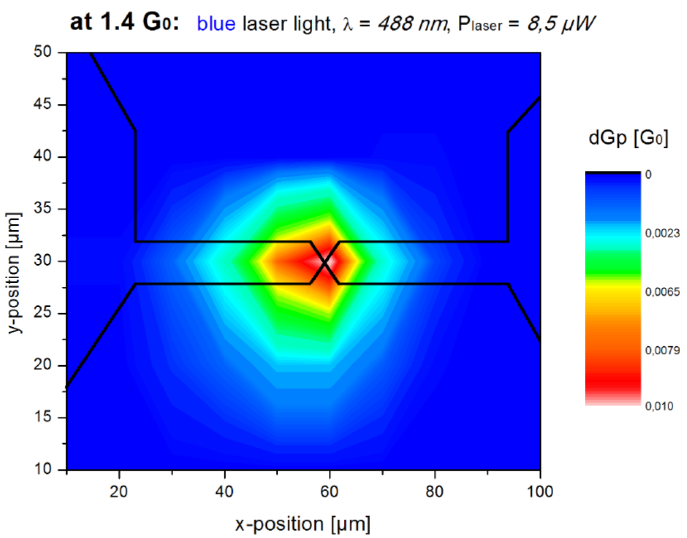
D. Guhr et al., Phys. Rev. Lett. 99, 086801 (2007)



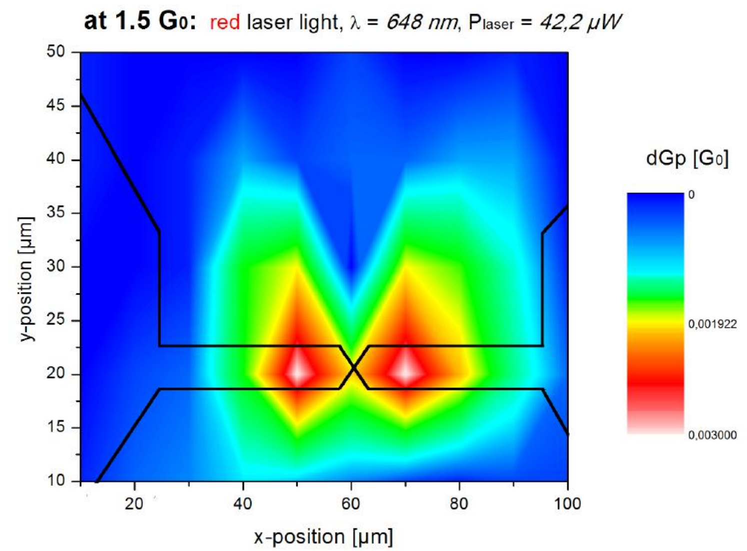
Light-induced Conductance Change

Scanning the focus across the break junction (Au)

Illumination at 488nm



648nm



Interpretation: at 648nm plasmons are excited in the leads, which propagate into the contact area

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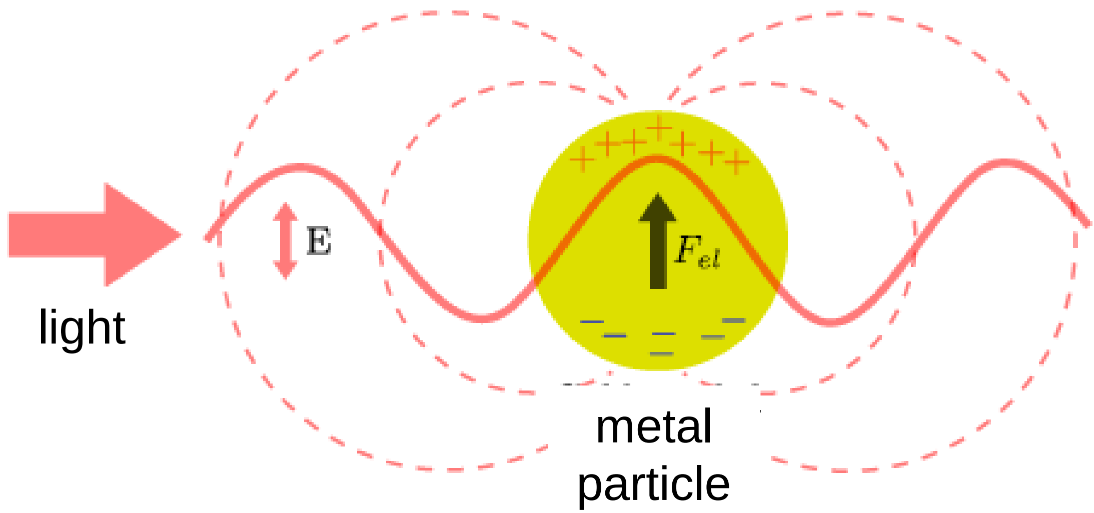
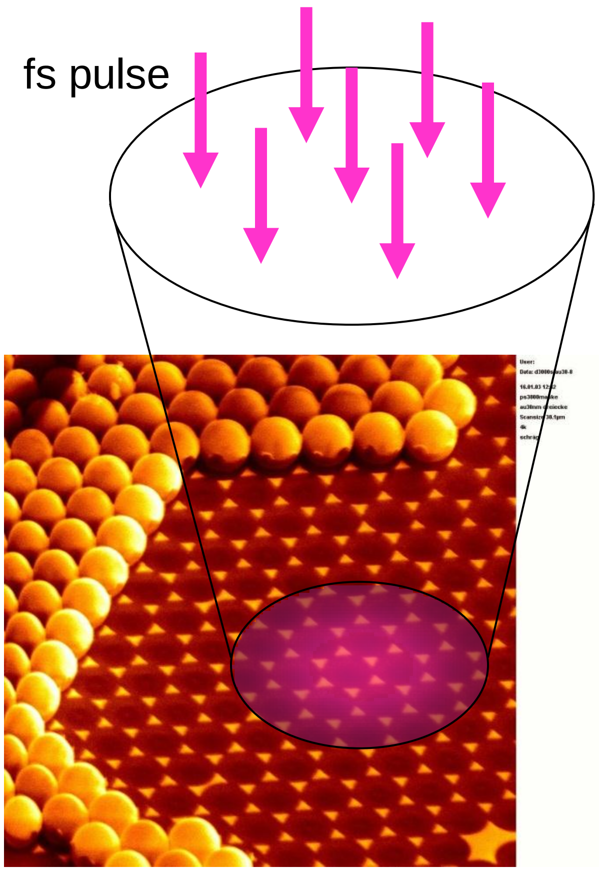
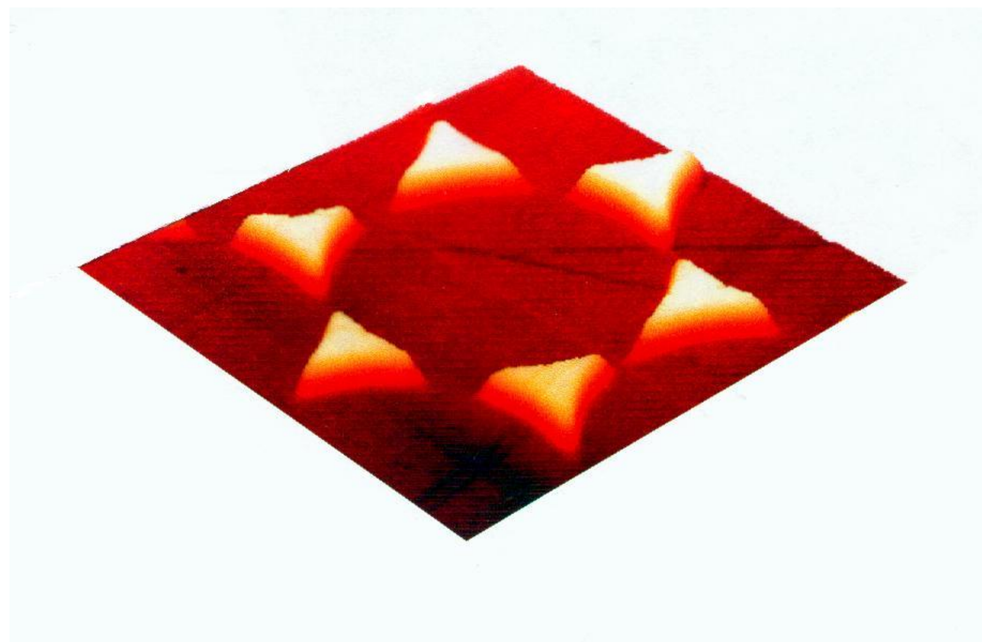


E
F_{el}
light
metal
particle

Near-field Distribution of Au Triangles

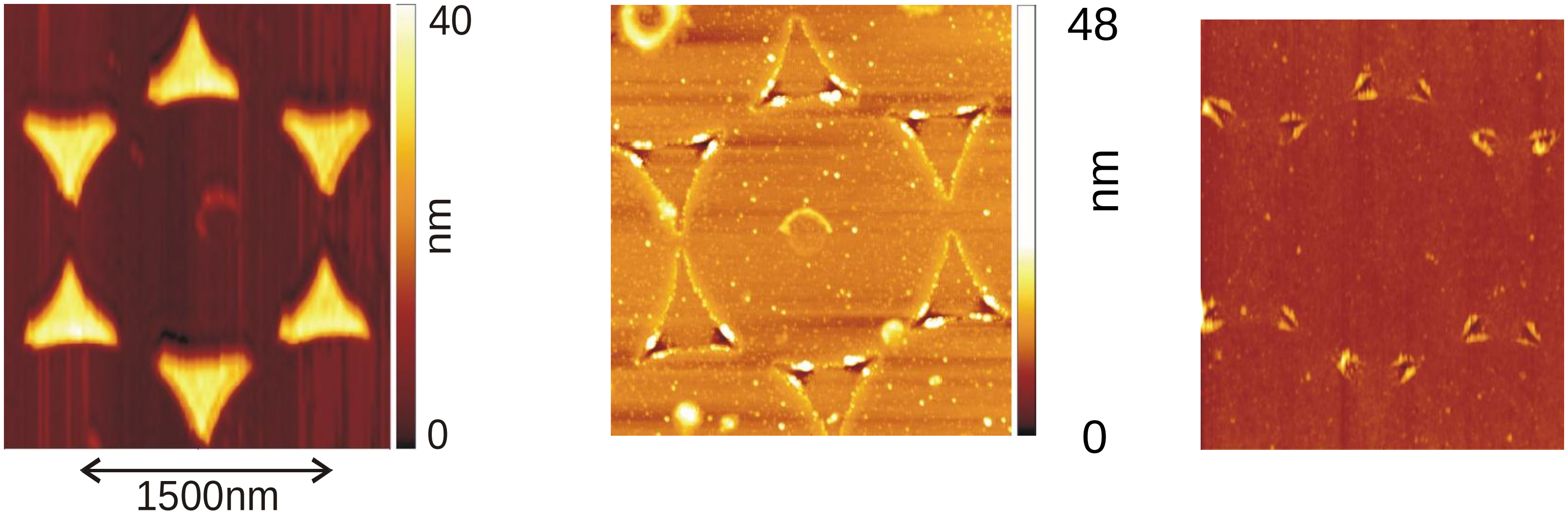




film thickness 40nm,
substrate: glass or Si

Optical Near-fields of Metal Nanostructures

Au on Si: “near-field photography“ (with 150fs laser pulse, 800nm)



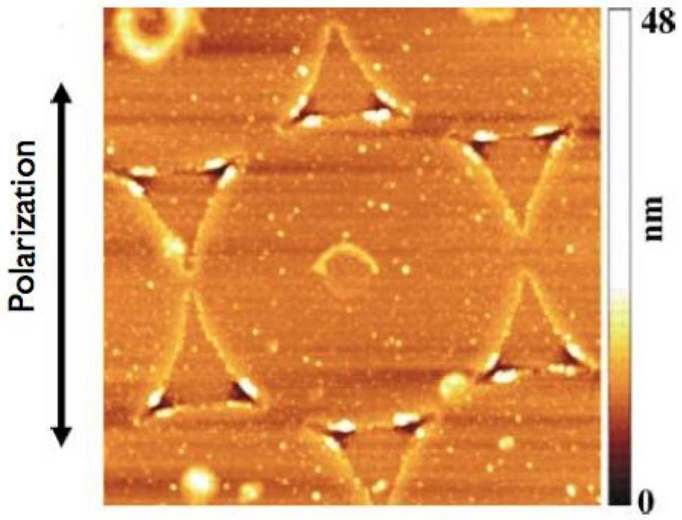
before ablation after ablation after etching Au

P.L., C. Bartels et al., Appl. Phys. Lett. **85**, 5372 (2004)

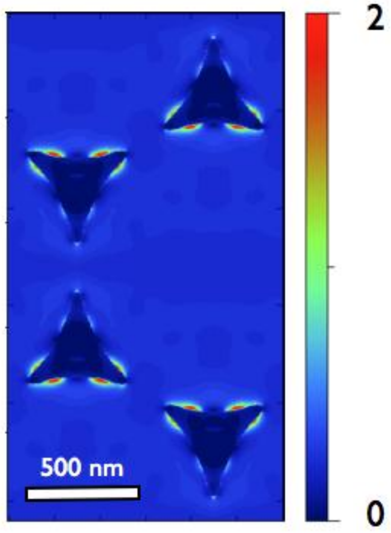
Comparison with FDTD Simulations

(Finite Difference in the Time Domain)

500nm Au structures on Si, irradiated with 800nm fs laser pulse



Ablation experiment for gold triangles with 40 nm Au thickness on Silicon



Simulated electric-field of gold triangles with 40 nm Au thickness on Silicon (+ 4 nm natural oxide-layer)

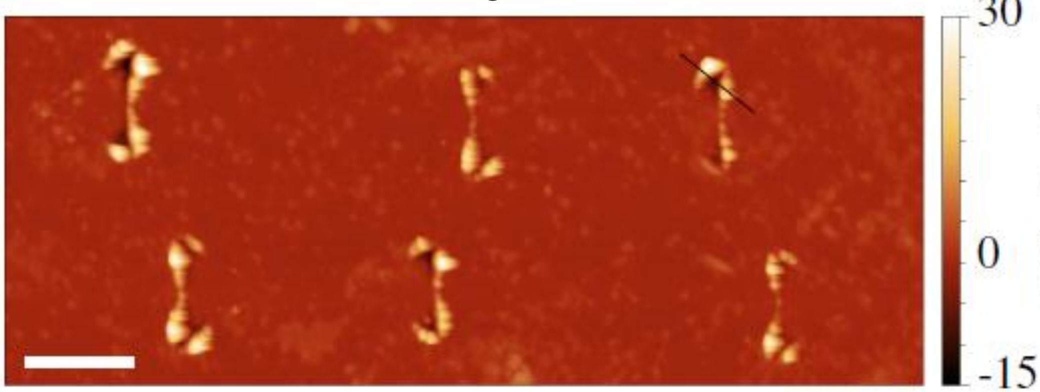
quadrupole mode!

⇒ good agreement in the near field distribution between simulations and experiment

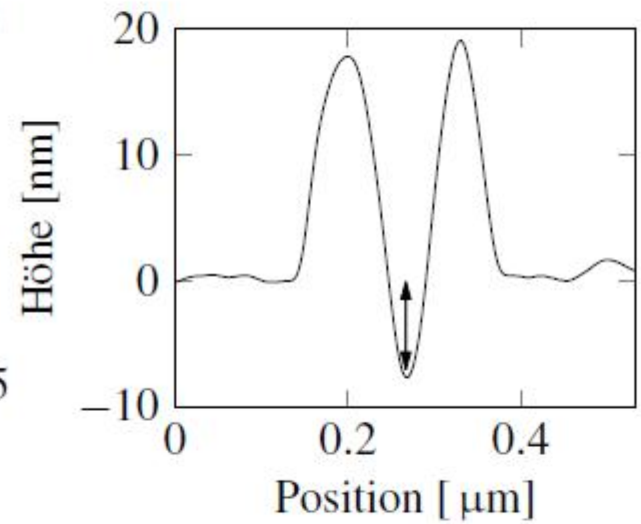
(if one takes into account details of the structure and the substrate, like the curvature of the „triangles“ and the SiO_2 surface layer)

Optical Nearfield Enhancement: Quantitative Determination by Local Ablation

245 mJ/cm^2 ⟵ increasing fluence 215 mJ/cm^2



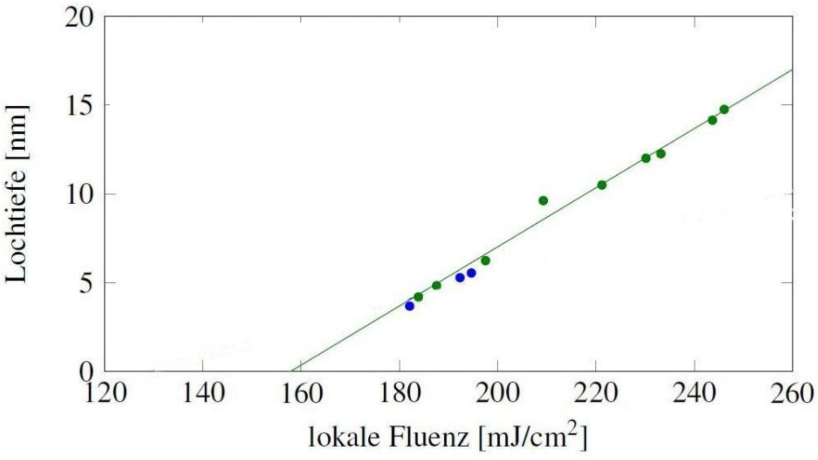
500nm polarization ↔



Optical Nearfield Enhancement: Quantitative Determination by Local Ablation

Depth of ablated hole

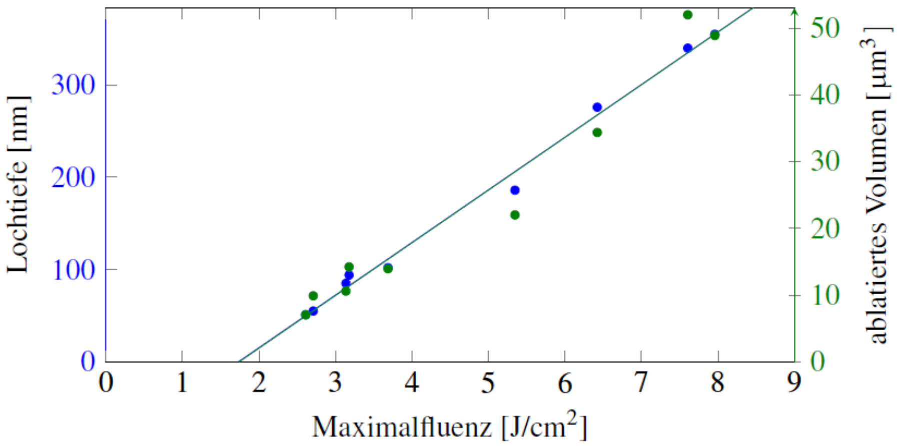
- by ablation using the near field enhancement at the triangle tip



- by ablation using a focussed laser beam in the far field (focus 30µm)

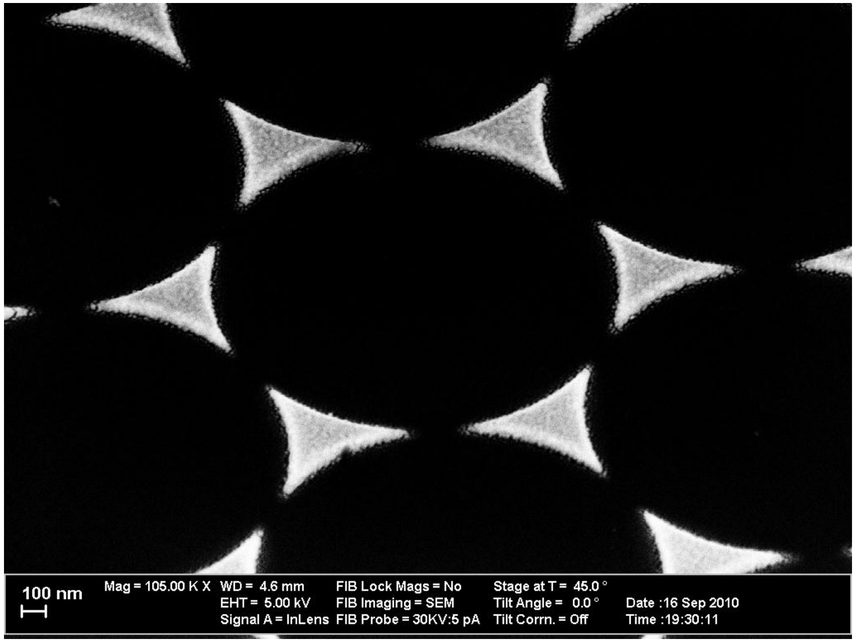
↓

Enhancement factor ~ 11
(quadrupole mode)

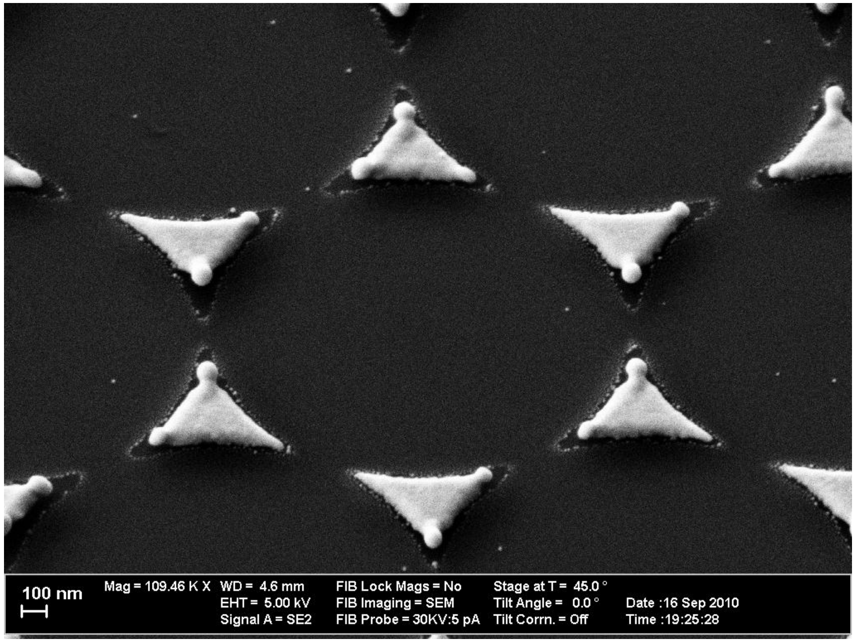


Effect of ps Pulses?

Au triangles on Si



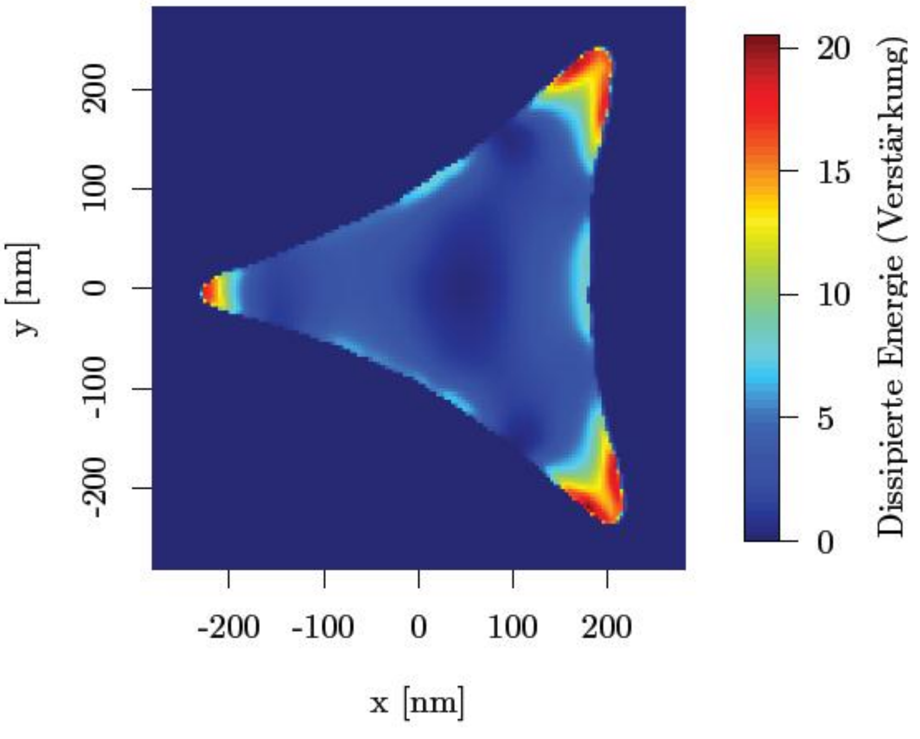
after irradiation with ps laser pulse



A. Kolloch et al., Appl. Phys. A (2011)

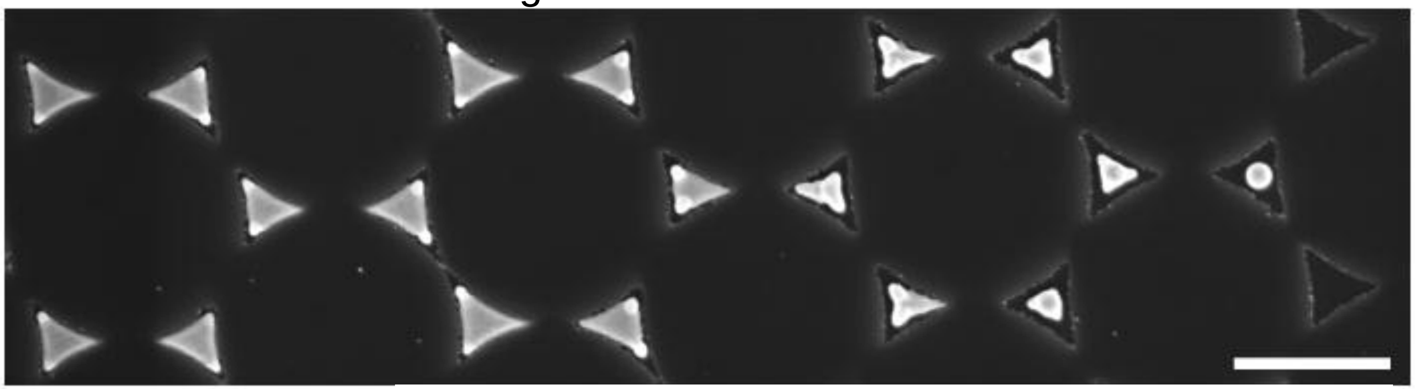
Optical Nearfield Enhancement: Quantitative Determination

Simulation for locally dissipated energy
(amplification compared to a smooth gold film))



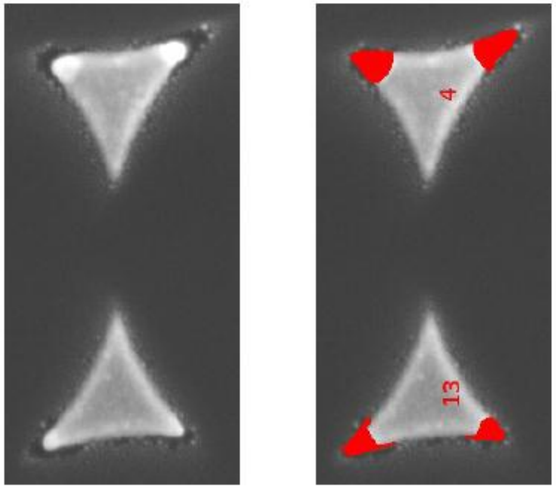
Optical Nearfield Enhancement: Quantitative Determination by Local Melting

85 mJ/cm^2 increasing fluence ⟶ 185 mJ/cm^2

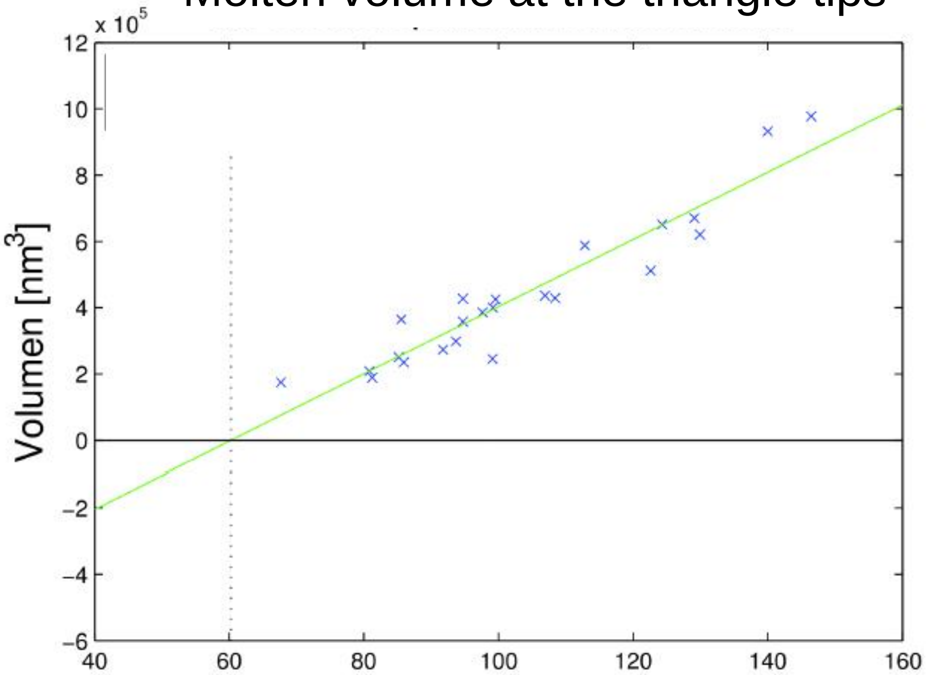


polarization ↔ 1µm

Optical Near Field Enhancement
determined by local melting



Molten volume at the triangle tips



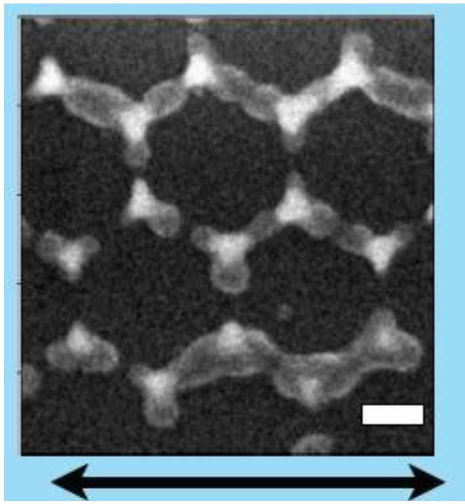
local fluence of laser pulse [mJ/cm^2]

Melting threshold for triangle tips: 60 mJ/cm^2
Melting threshold of the unstructured gold film: 550 mJ/cm^2

⇒ amplification factor ~ 9

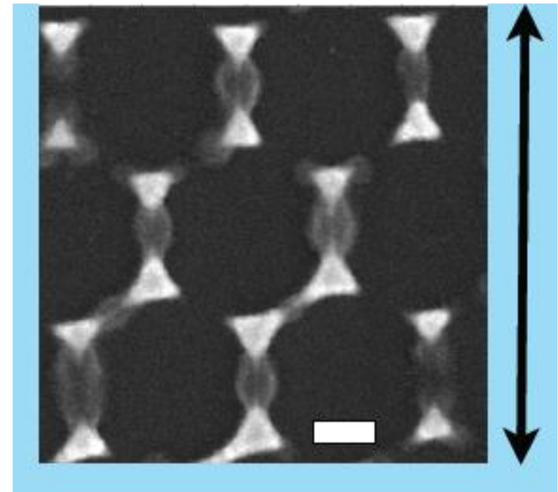
Near Field Imaging by Two-Photon Polymerization

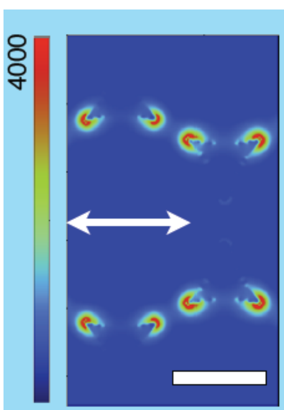
using the nonlinear intensity dependence of SU8 polymerization for 800nm light



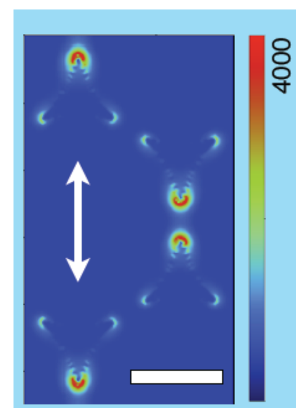
2-Photon Polymerization
for different polarizations
(indicated by the arrows)

Experiment





FDTD
calculation



(scale bars 100 nm)

Dipole mode ⇒ amplification factor ~ 600±140

T. Geldhauser et al., Plasmonics **6**, 207 (2011); Langmuir **28**, 9041 (2012)

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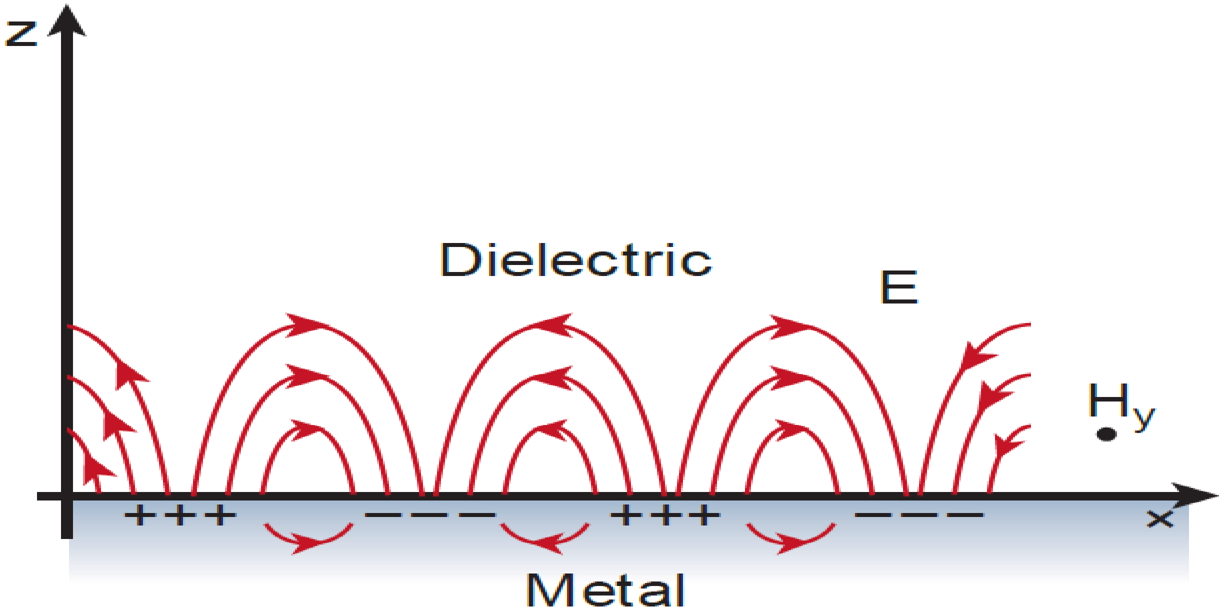
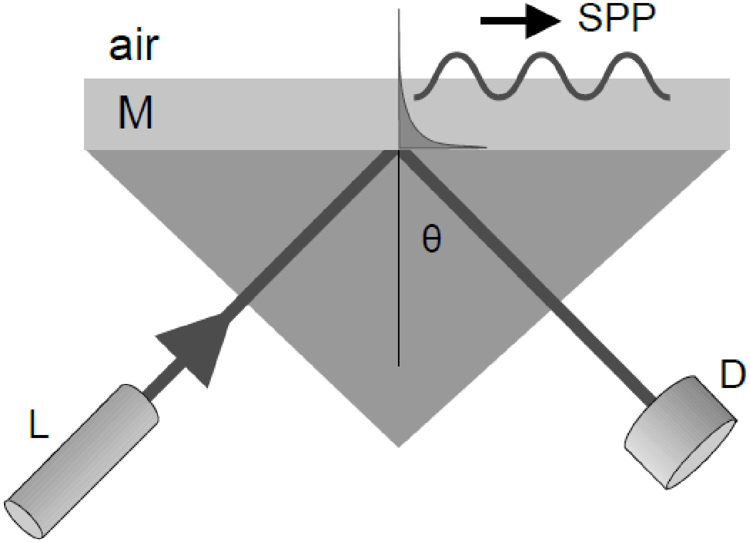
Propagating Surface Plasmon Polariton

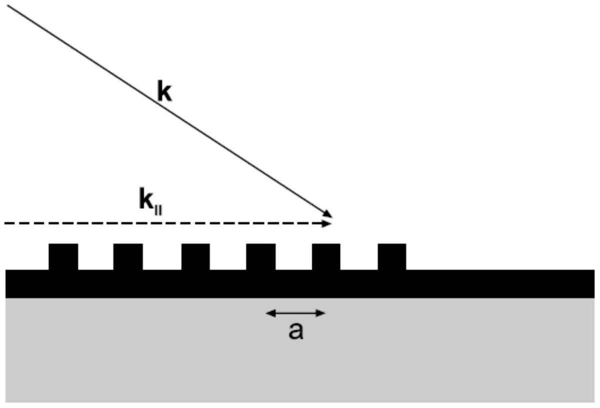


Excitation of Surface Plasmons with Photons

Problem: matching the wave vectors of plasmon and photon
(excitation on a smooth metal surface is not possible)



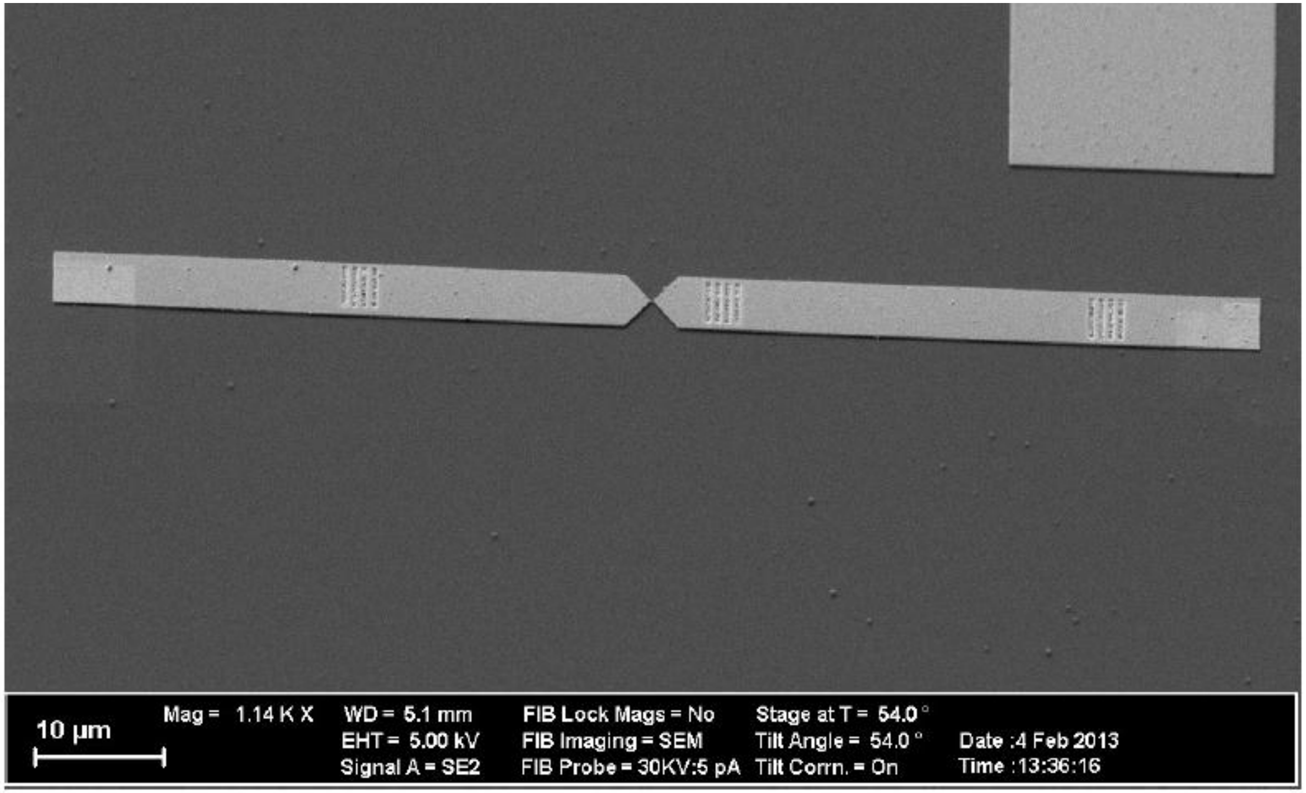
coupling via prism
(Kretschmann configuration)



coupling via grating

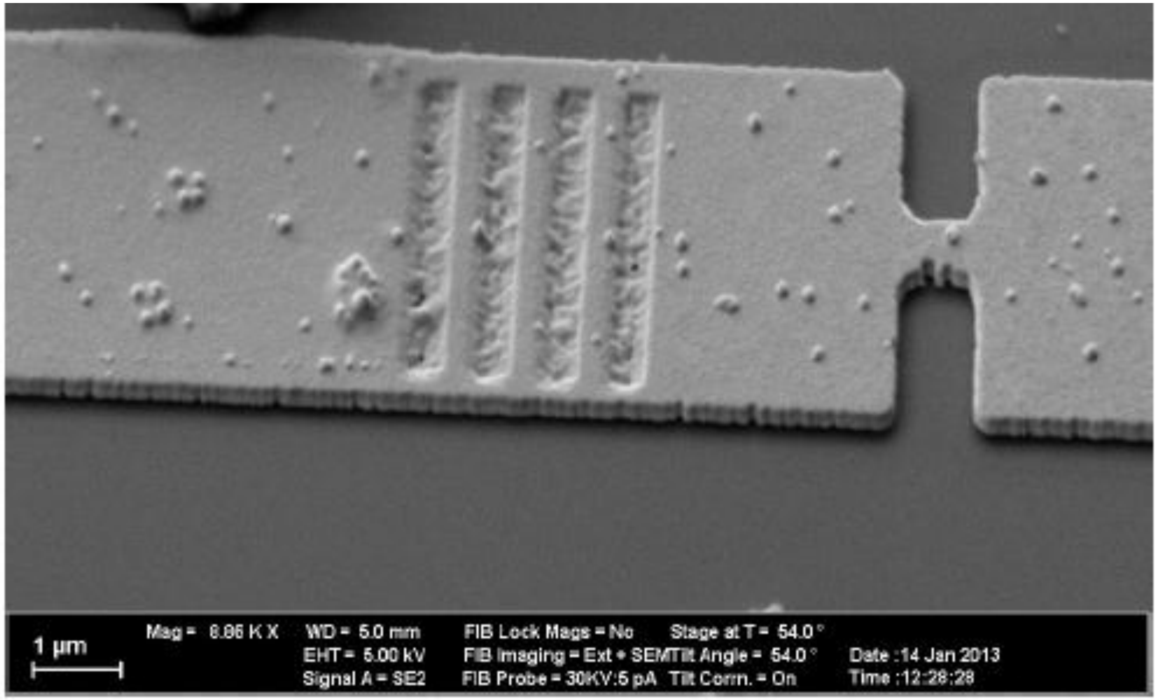
Gold Structure on Thin Si Membrane

Si: 340nm thick
Au: 40nm
Design: MCBJ

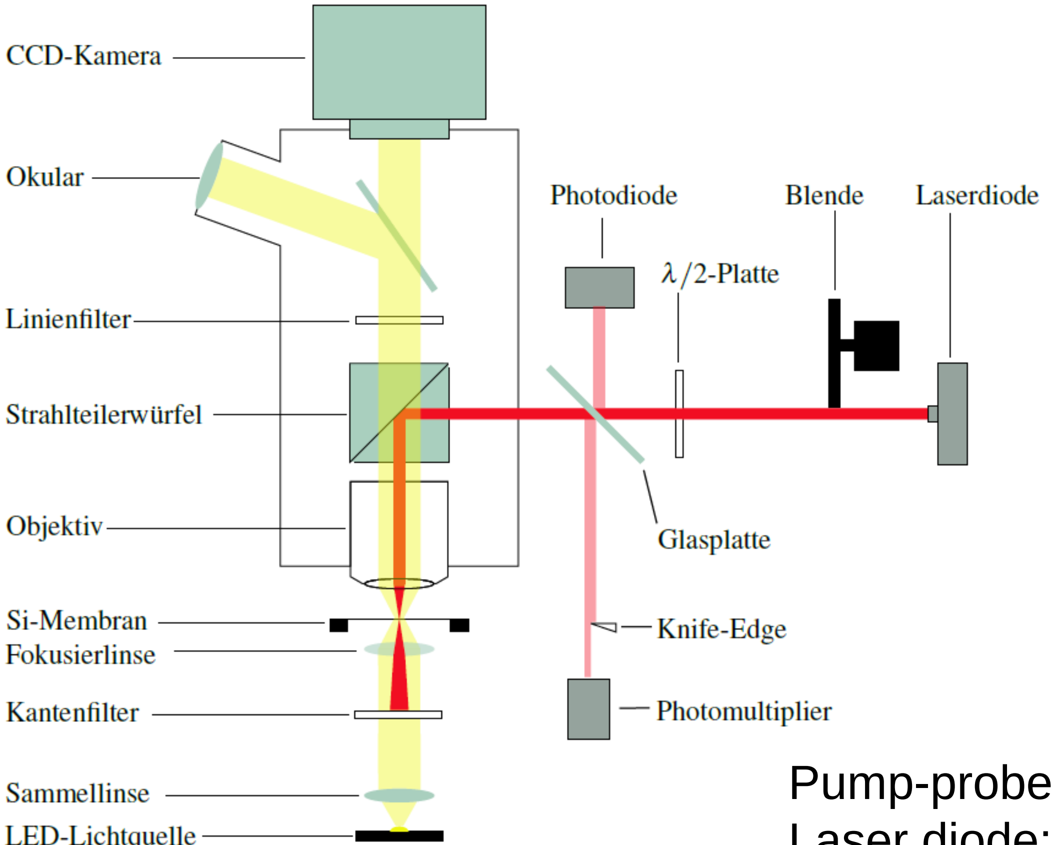


Grating for Plasmon Excitation

generated with Focussed Ion Beam



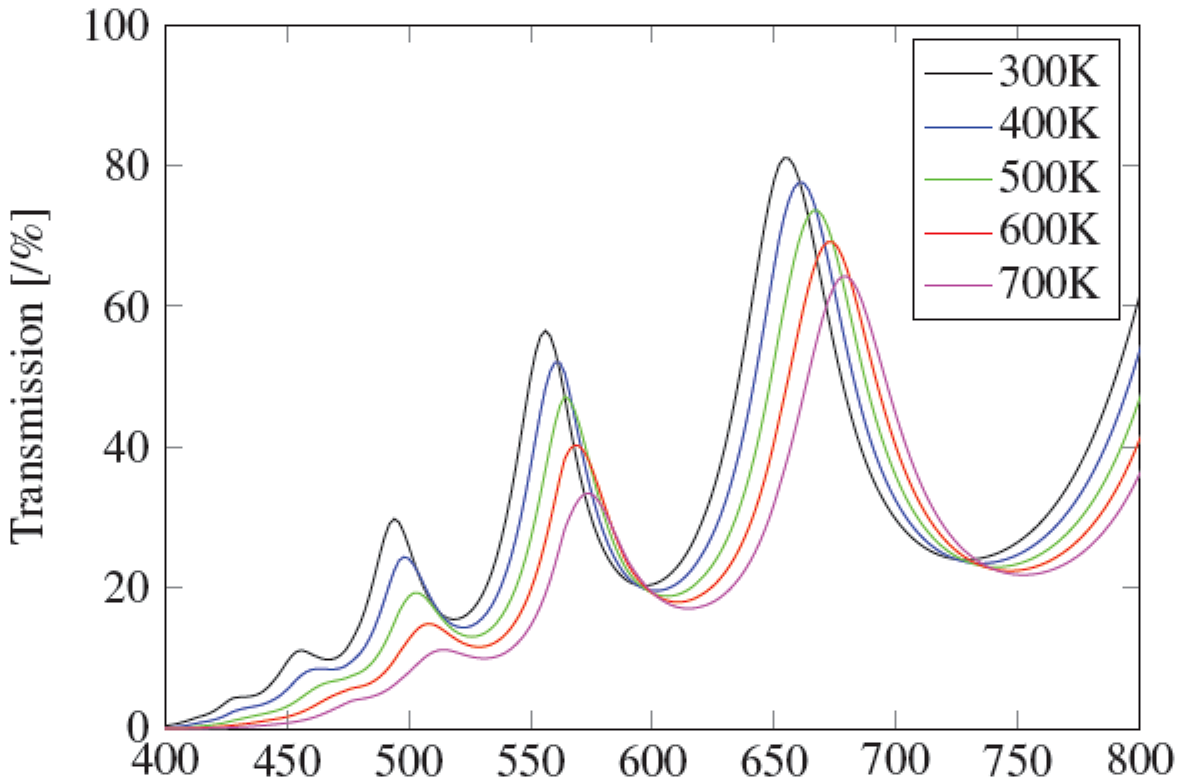
Optical Set-up



Pump-probe technique:
Laser diode: pump
LED: probe
(presently: 100ns resolution)

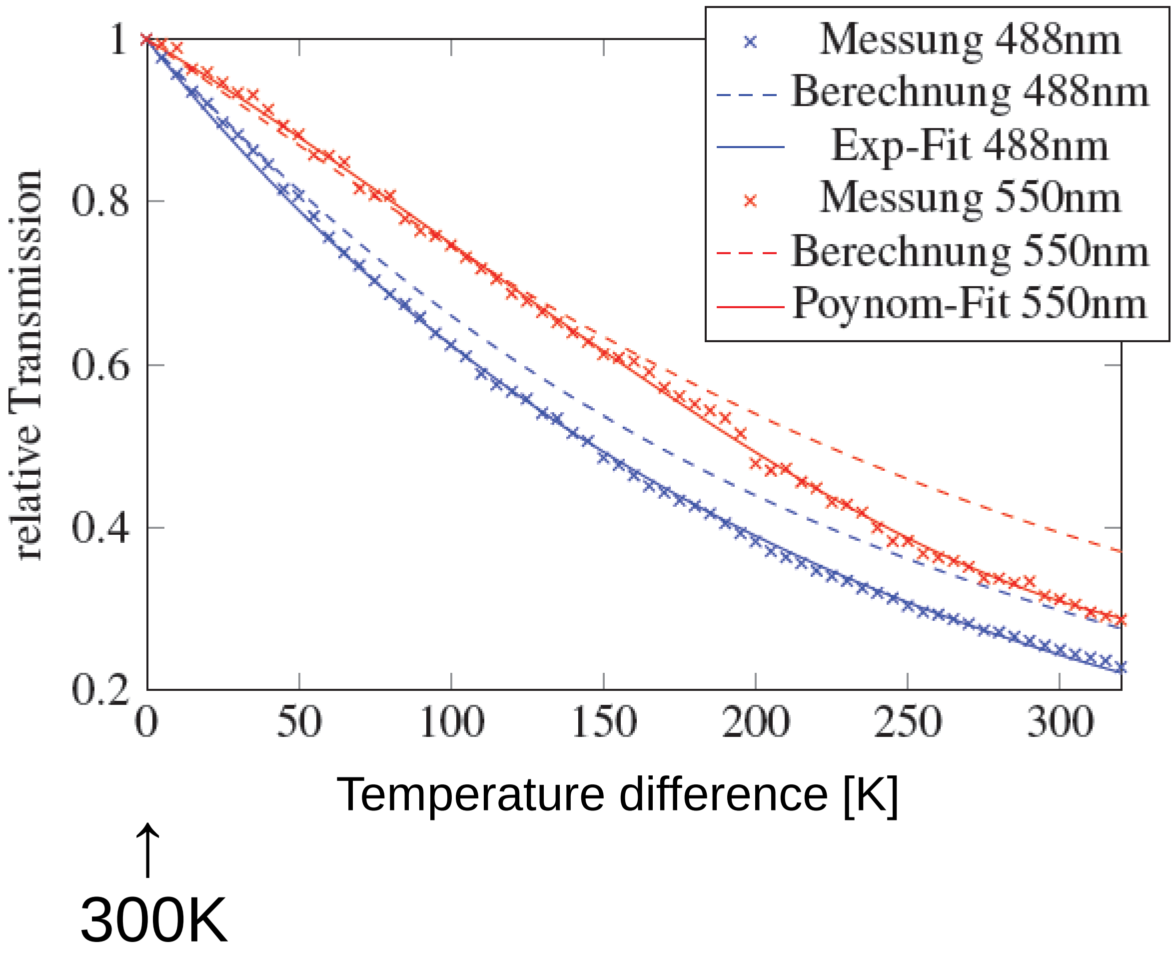
Spectral Transmissivity of Si Membranes

340nm thick



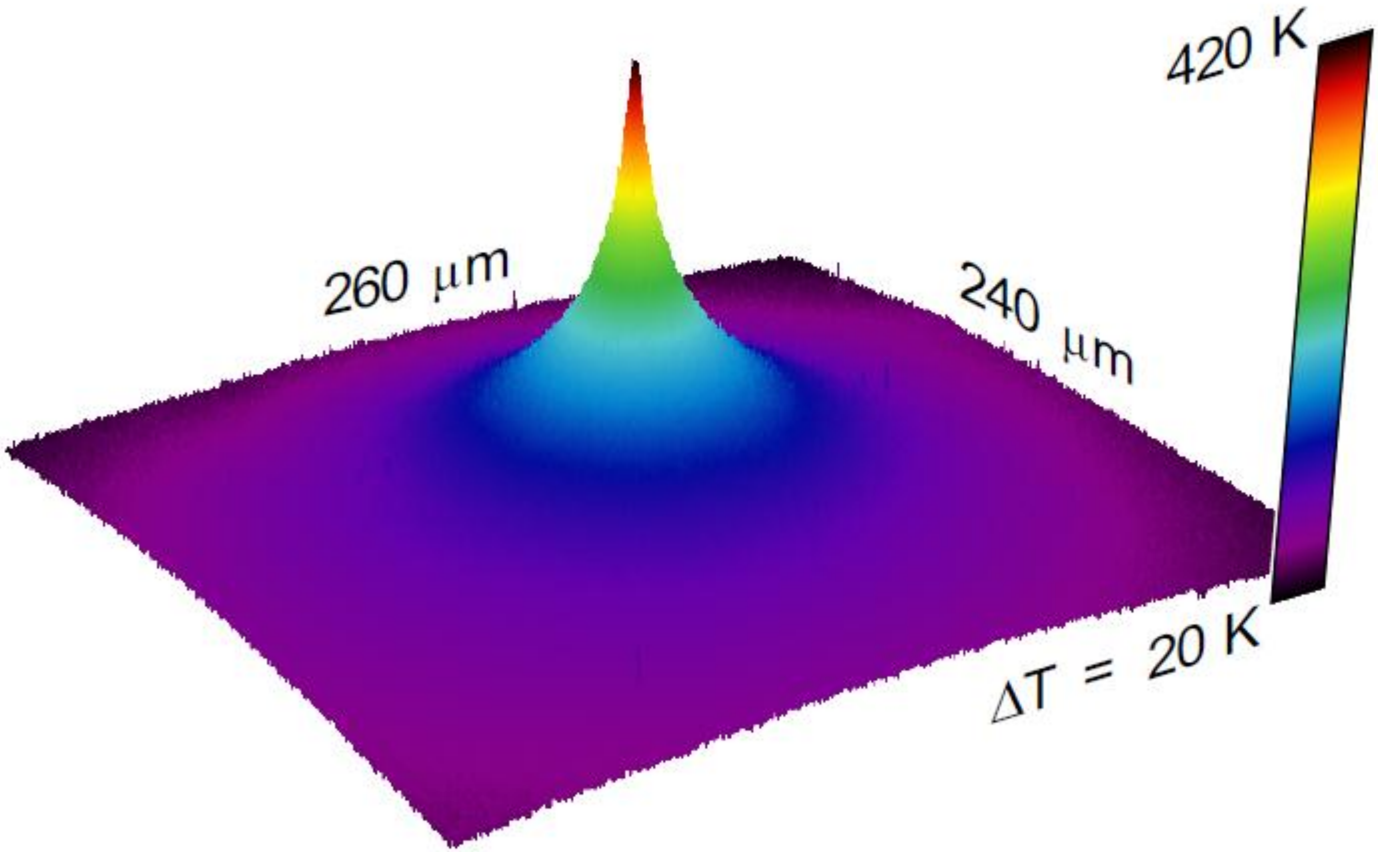
Wavelength [nm]

Temperature Dependence of the Optical Transmissivity

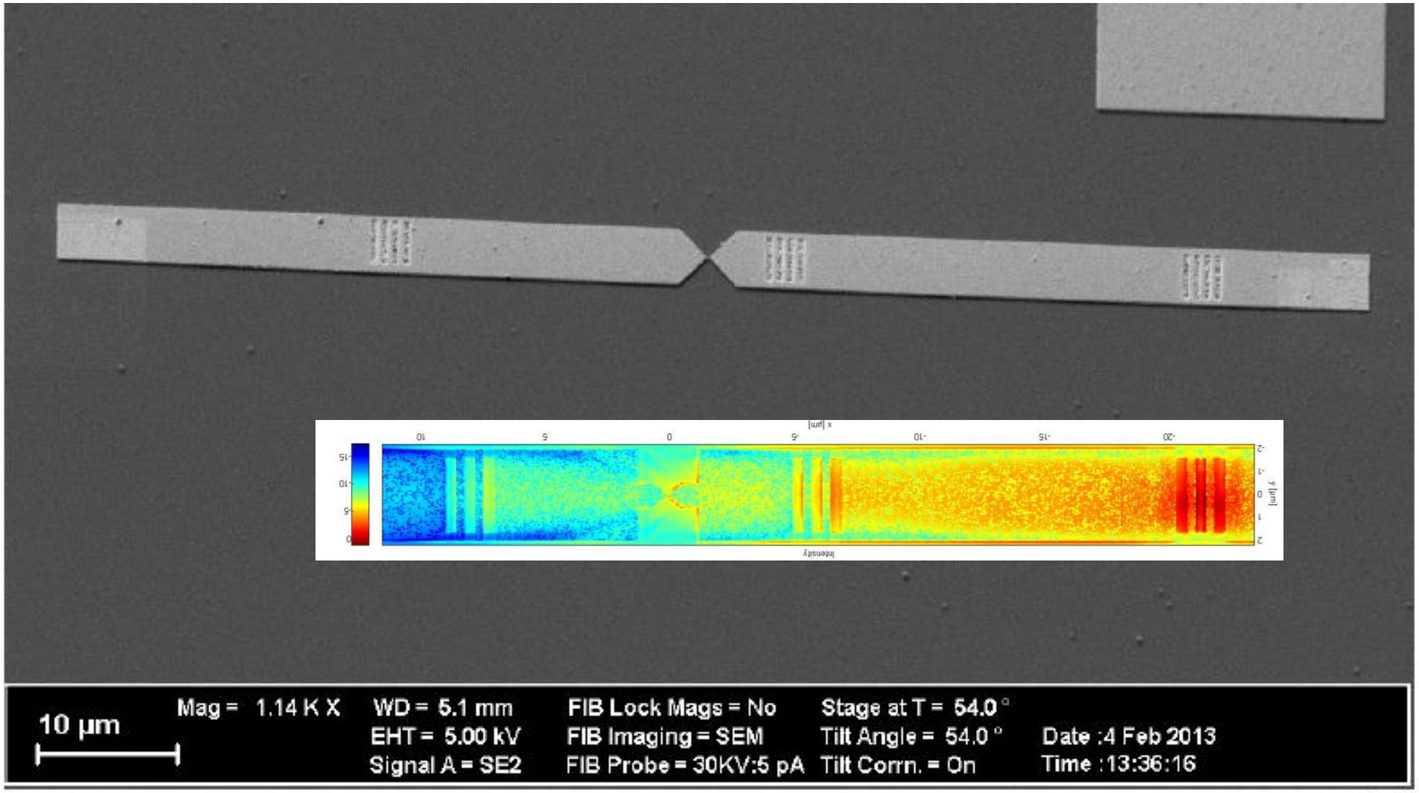


Temperature Map

of a membrane which is heated in the centre by a focussed laser beam



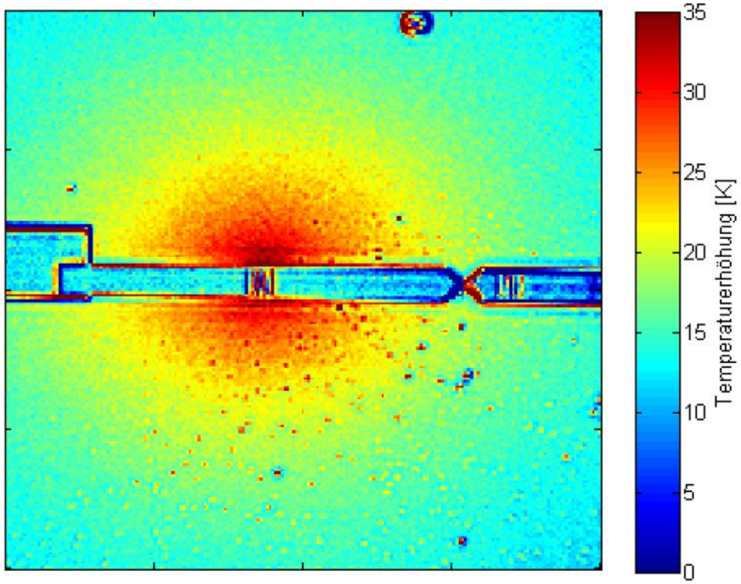
Plasmon propagation along strip?
Influence of the constriction?



Insert: Simulation by Golaleh Ghafoori

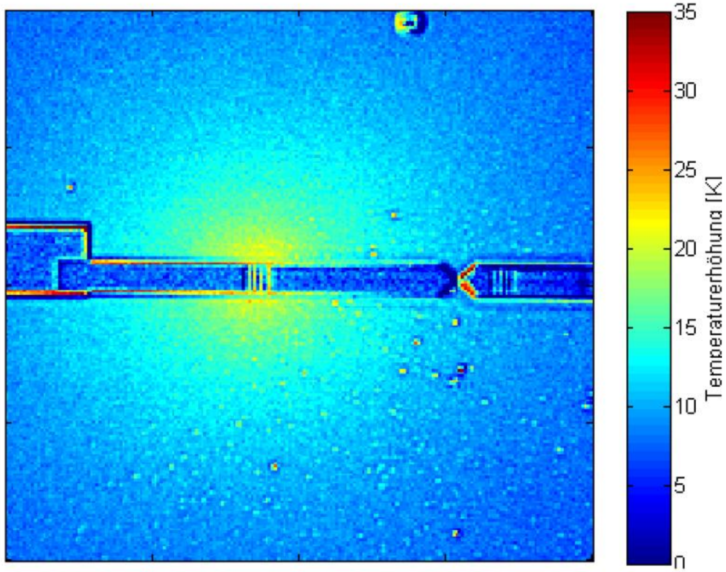
Heating the Grating
with a focussed laser beam

polarization horizontal



calculated absorption: 19%

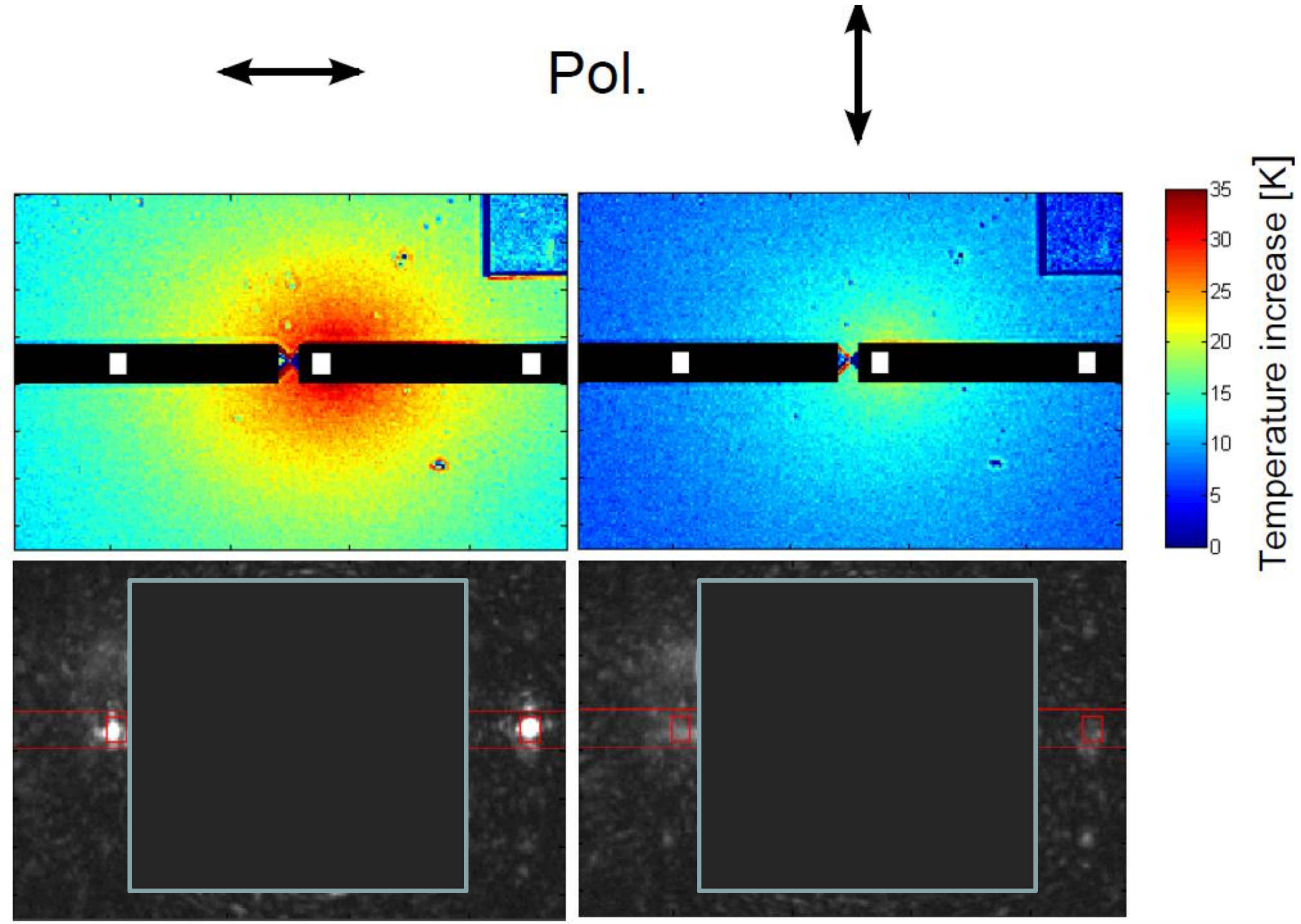
polarization vertical



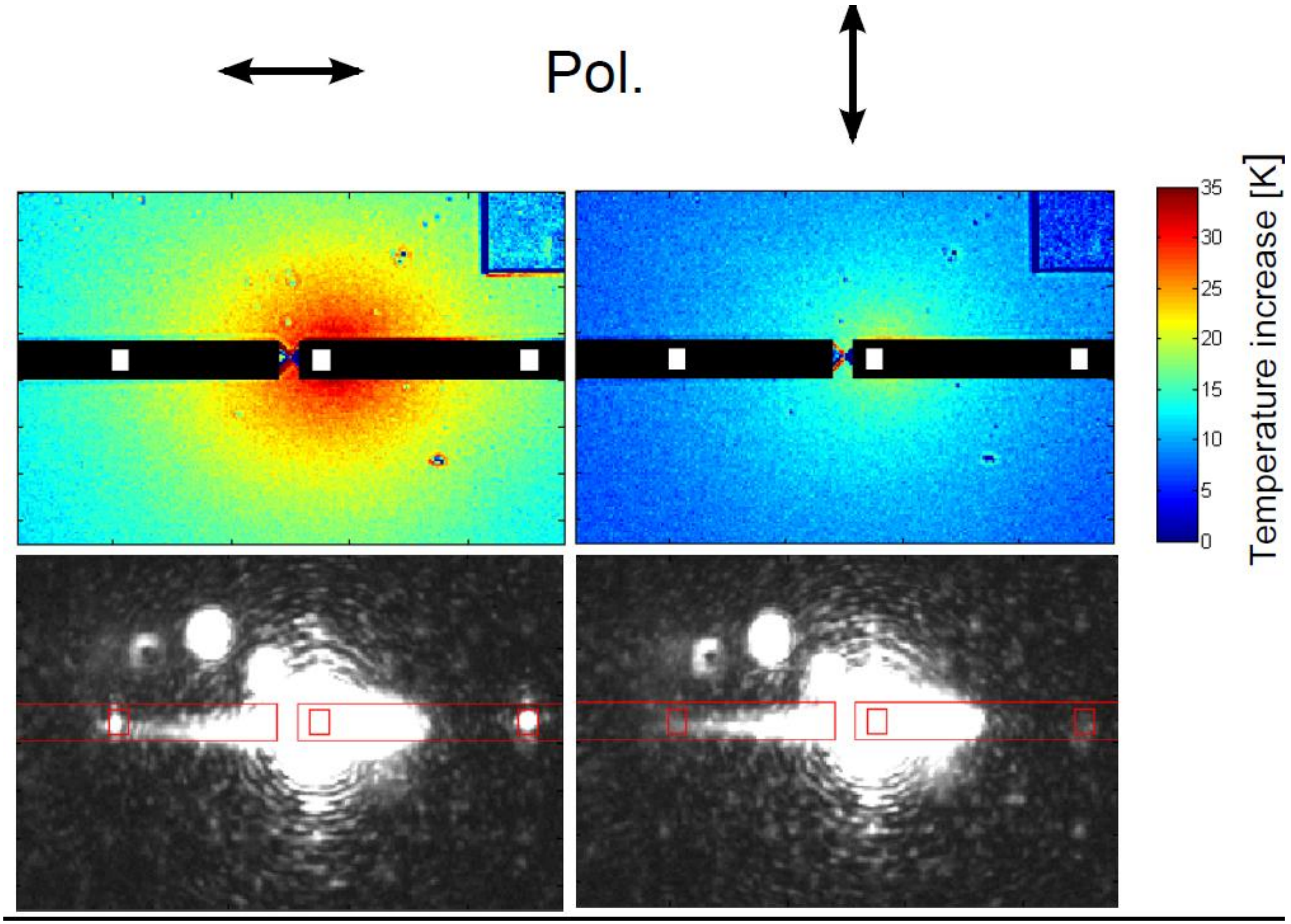
calculated absorption 11%

⇒ coupling is strongly enhanced by the grating

Propagation of Plasmons ?

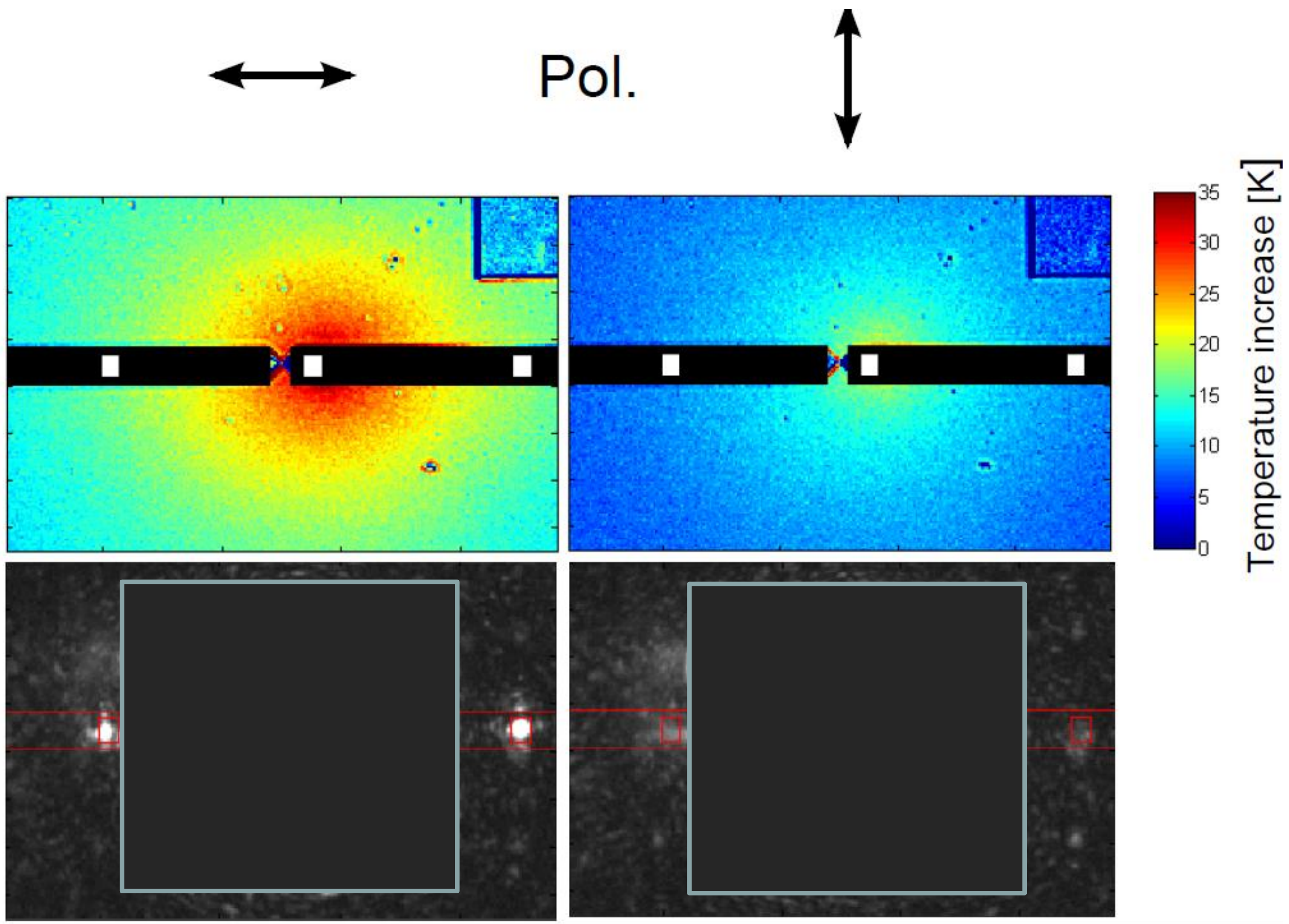


Propagation of Plasmons



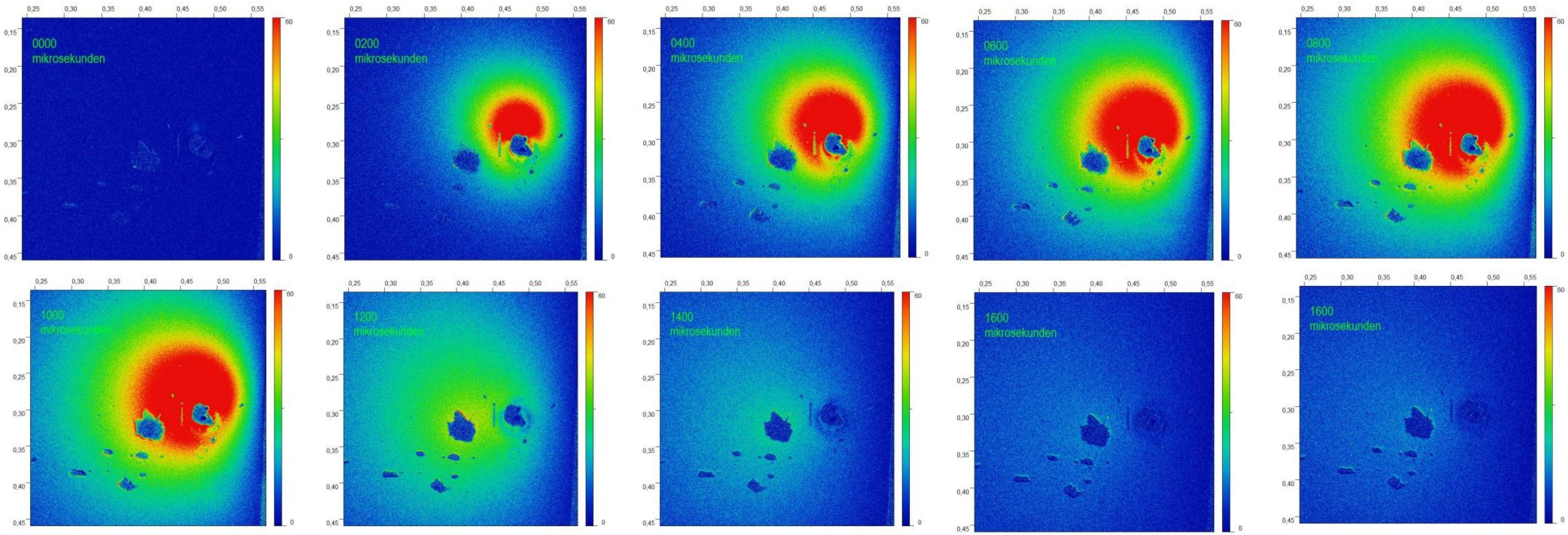
Scattered light in optical microscope

Propagation of Plasmons



Indium Particles on a Si Membrane, heated by a 1000µs laser pulse

(example for a time-resolved measurement

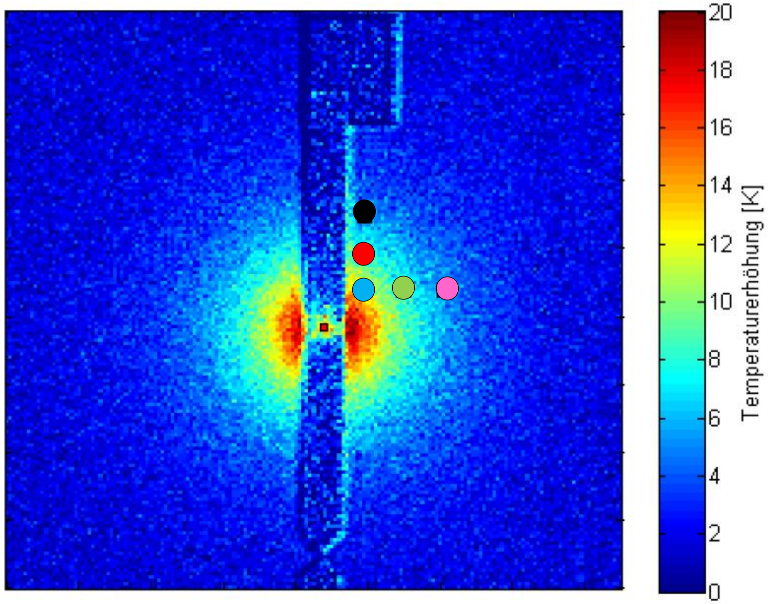


Sequence taken at time intervals of 200µs

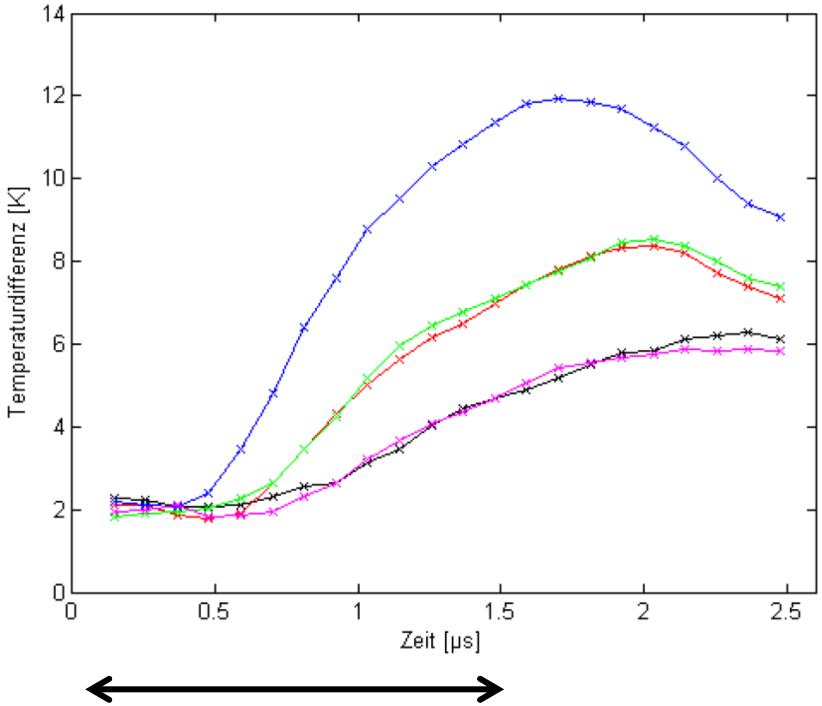
Time-resolved Measurements

Light polarization horizontal (i.e. parallel to grating bars)

temperature map at t=1.5µs



time evolution at different positions

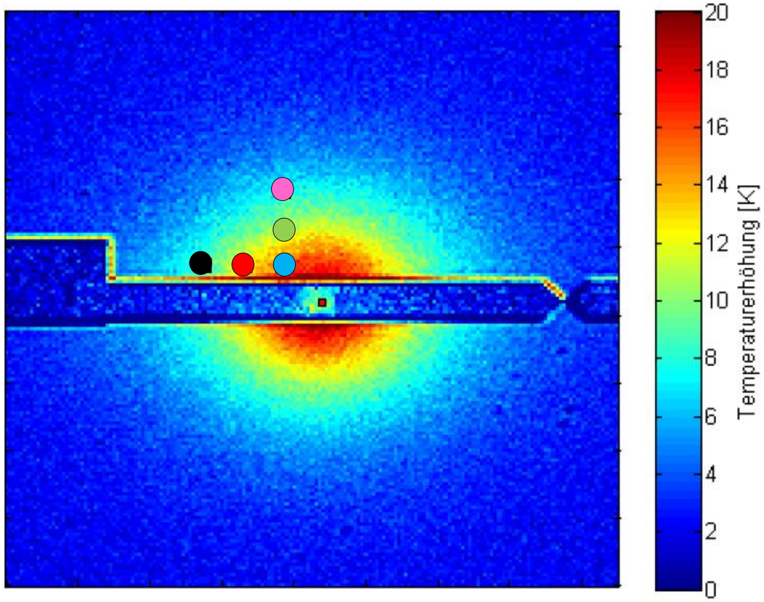


laser pulse

Time-resolved Measurements

Light polarization horizontal (i.e. parallel to grating bars)

temperature map at t=1.5µs



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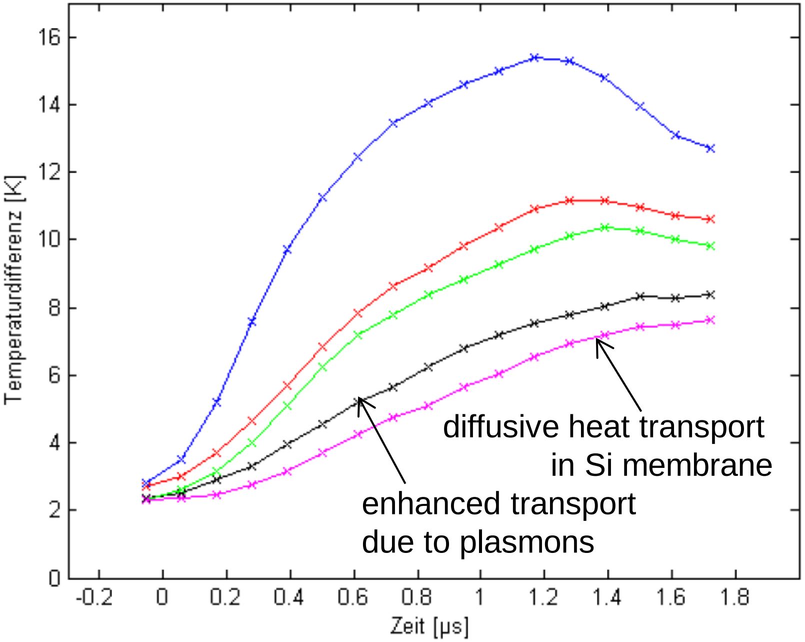
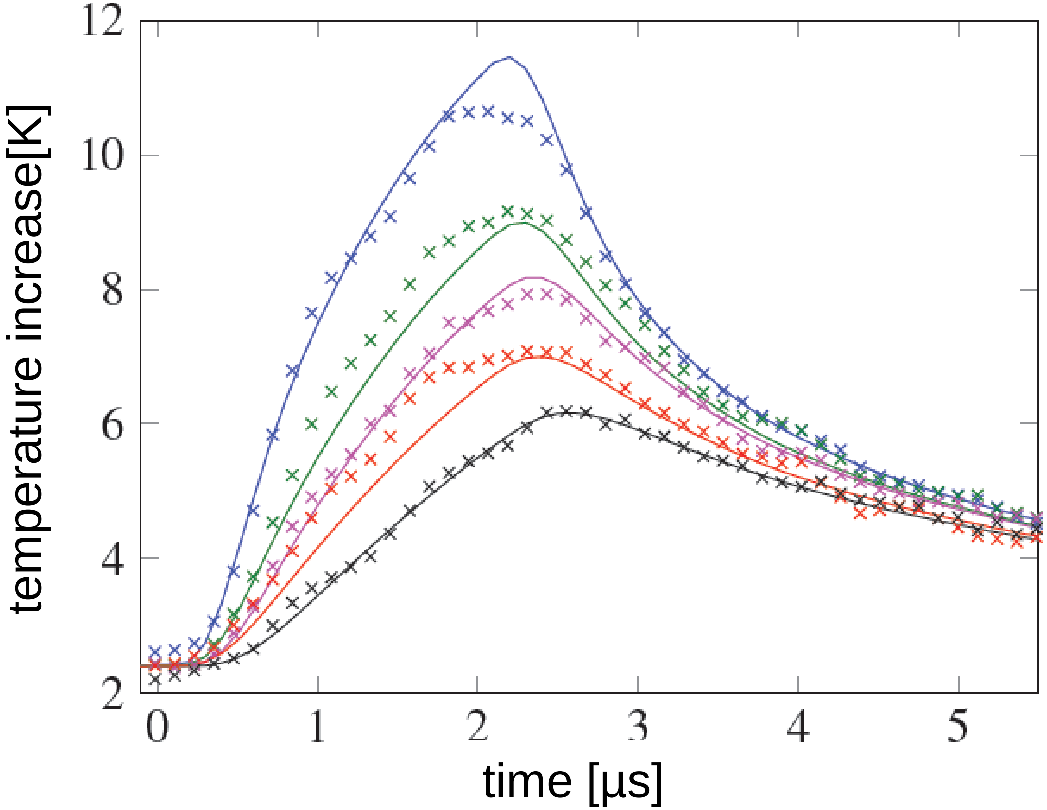


Comparison with Simulation



Crosses: experiment (laser pulse width 2µs)
Lines: simulation using COMSOL Multiphysics (heat source defined by a simulation using Lumerical FDTD)

Conclusions

- Plasmon resonances in metallic nanostructures can lead to strong (local) enhancement of the electromagnetic field

- The optical near field distribution can be imaged by various techniques, e.g.

    - local ablation of proper substrates (e.g. smooth Si wafers)
    - local melting
    - 2-photon polymerization
    - …

- The enhancement can be localized to $d \ll \lambda_{light}$

- Good agreement with FDTD calculations has been obtained
    - for the spatial distributions
    - enhancement factors? (under investigation)

- Plasmonic effects on conductivity, nanostructuring, nanomelting, spin-plasmonic devices …

+++++++++++++++++++++++++

- Si membranes are efficient thermometers: high temporal and spatial resolution

Thanks to …

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