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Laser ablation – fundamentals and application

Laserová ablace – principy a použití

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Optické komunikace a WDM Systems Summit 2014,
23. a 24. října 2014 - ČVUT v Praze, FEL

What is **ablation**?

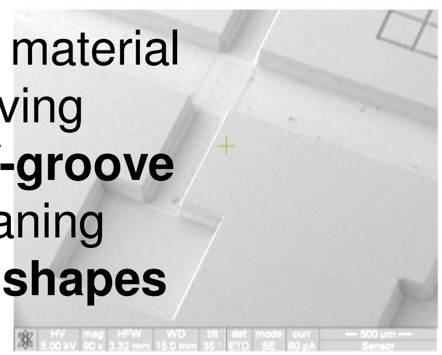
- *process of removing material from a solid material*
- can refeer to tough diamond or metals on one hand, and soft ceramics or glass

What is **ablation rate**?

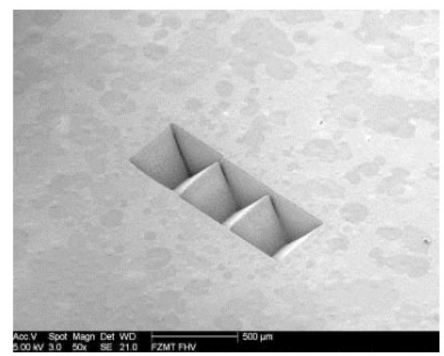
- total mass ablated from the target per laser pulse can be referred to as **ablation rate**

What is it good for?

- **cutting** the material
- laser engraving
- **drilling a V-groove**
- surface cleaning
- printing **3D shapes**



Microfluidic sensor: Selective ablation of photoresist on glass



3D-structure in glass, 1000 x 400 μm, τ = 300 fs, λ = 1040 nm

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What **parameters** influence ablation?

- threshold **fluence**
- **energy penetration depth**
- laser **pulse duration**
- laser's wavelength
- optical-thermal properties of material to be processed

but…

- laser pulse properties can be **getting different**, as the pulse is **propagated** in the V-groove

Ablation depth

$$z = \delta \cdot \ln\left(\frac{\phi_a}{\phi_{th}}\right)$$

*B. **Neuenschwander**, B. Jaeggi, M. Schmid, V. Rouffiange and P. E. Martin, "Optimization of the volume ablation rate for metals at different laser pulse-durations from ps to fs," in 2012 Proc. Laser Applications in Microelectronic and Optoelectronic Manufacturing, doi:10.1117/12.908583.*

ablation depth z is function of

- fluence ϕ_a
- threshold fluence ϕ_{th}
- energy penetration depth δ

What is **fluence**?

- radiative flux integrated over time
- lasers are specific for their flux
- related to pulse duration (milliseconds to femtoseconds)

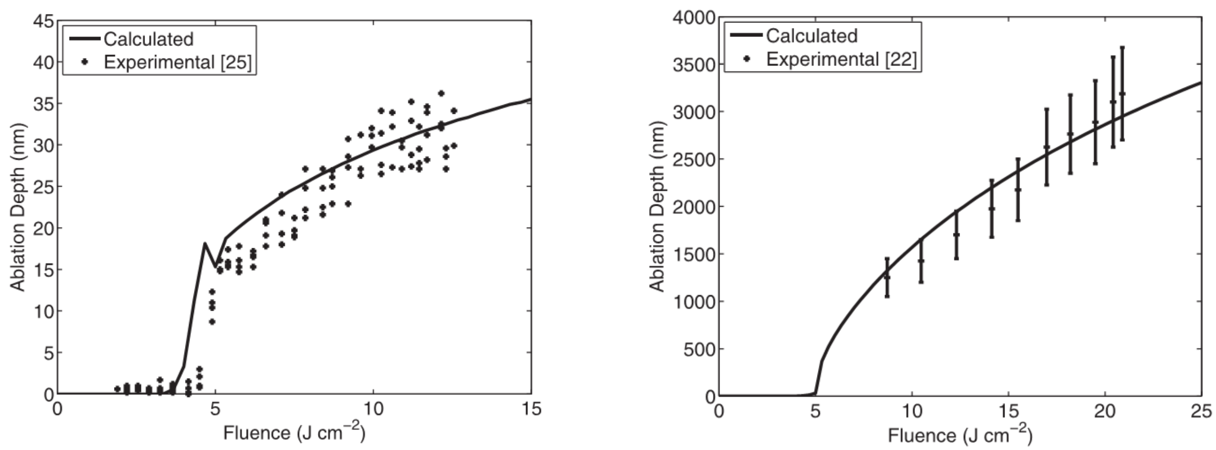
What is **penetration depth**?

- depth over which the laser energy is absorbed
- depends on the material properties
- depends on the pulse length

Ablation depth

ablation depth *z* is function of

- fluence ϕ_a, threshold fluence $\phi_{th.}$energy penetration depth δ
- is nonlinear and varies with pulse length



Pulse duration 5 ns (left) and 10 ns (right). Λ=1064 nm

A. Lutey: An improved model for nanosecond pulsed laser ablation of metals, Journal of Applied Physics 114, 083108 (2013)

Ablation depth

$$z = \delta \cdot \ln\left(\frac{\phi_a}{\phi_{th}}\right)$$

- it is threshold fluence and penetration depth that are actually responsible for ablation efficiency

Two regimes possible:

- low fluence is applied but energy **penetration depth is still efficient**
- **fluence is significantly higher** and dominating due to higher energy transfer

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Lasers for ablation

- low price lasers emitting **nanosecond** pulses (from few to tenths of nanoseconds) - low laser flux

B. N. Chichkov, C. Momma, S. Nolte, F. von Alvensleben and A. Tünnermann, „Femtosecond, picosecond and nanosecond laser ablation of solids,“ Appl. Phys. A 63, 109, 1996.

- more expensive **femtosecond** pulse lasers (so-called cold ablation)

T. Rublack, M. Muchow, S. Hartnauer, and G. Seifert, “Indirect lift-off of thin dielectric layers from silicon by femtosecond laser ‘cold’ ablation at the interface,” CLEO: 2013, OSA Technical Digest (Optical Society of America), pp. CM4H.6, 2013.

Nanosecond lasers

$$I = \lim_{\Delta t \to 0} \frac{\Delta q}{\Delta t}$$

I is the flow of quantity (in general) per unit of time ***t*** and ***q*** is the area through which the quantity flows.

- material is heated
- evaporates through liquid into gas
- sublimates directly from the solid to gas

Nanosecond lasers

$$I = \lim_{\Delta t \to 0} \frac{\Delta q}{\Delta t}$$

- relatively long pulse duration
- flow rate is a measure of heat transfer per time
- low laser flux
- **low ability to ablate material**

- nanosecond lasers can emit higher power

but…

- **power must be referred to *t***
- ablation depends as well on the penetration depth that can be worse for nanosecond pulse lasers

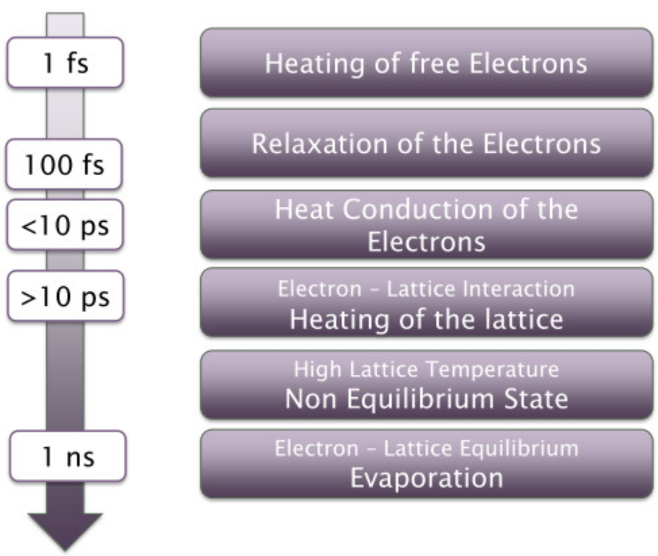
Femtosecond lasers

Light needs 1.25s for travelling the distance from the Earth to the moon

- high laser flux
- material is typically converted to plasma
- working in so-called **cold ablation** regime

Cold ablation - plasma shielding avoidance

T. Rublack, M. Muchow, S. Hartnauer, and G. Seifert, "Indirect lift-off of thin dielectric layers from silicon by femtosecond laser 'cold' ablation at the interface," CLEO: 2013, OSA Technical Digest (Optical Society of America), pp. CM4H.6, 2013.



- pulses carry huge energy
- thermal phase change of ablated material occurs after 1 ps or later
- material will not be overheated
- no collapse of shape or low depth of performed cut
- femtosecond lasers are short enough to overcome the plasma shielding

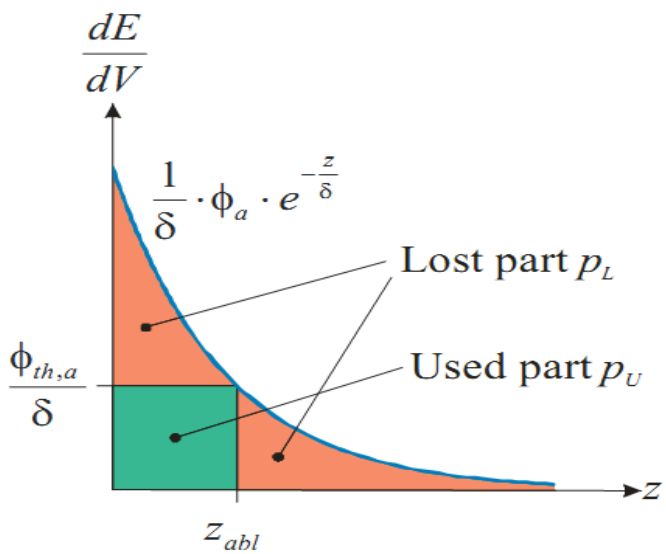
Ablation law

$$\frac{dE}{dV}(z) = \frac{1}{\delta}\phi(z) = \frac{1}{\delta}\phi_a \cdot e^{-\frac{z}{\delta}}$$

- ϕ_a is fluence absorbed
- **drop of the deposited energy *dE* per unit volume *dV* with distance *z* to the surface**
- energy drop is responsible for the evaporation process

but…

- not all the energy is used to evaporate material
- used energy limited by material and specific heat of evaporation
- different for different ablation depth



B. Neuenschwander, B. Jaeggi, M. Schmid, U. Hunziker, B. Luescher, C. Nocera, "Processing of industrially relevant nonmetals with laser pulses in the range between 10 ps and 50 ps," In Proc. of ICALEO 2011, paper M103, 2011.

- not all the energy is used to evaporate material
- used energy limited by material and specific heat of evaporation
- different for different ablation depth

Ablation efficiency improvement

$$\phi_{th}(\mathrm{N}) = \phi_{th,1} \cdot N^{S-1}$$

Y. Jee, M.F. Becker and R.M. Walser, "Laser-induced damage on single-crystal metal surfaces," J. Opt. Soc. Am. B 5, 1988.

- there are **incubation effects**
- different threshold fluence for different amount of laser pulses
- energy loss caused by plasma shielding is significantly reduced

- Threshold fluence $\boldsymbol{\phi}_{th}$ can be obtained as threshold value for one pulse multiplied by a coefficient that expresses number of pulses ***N*** and ***S*** their incubation coefficient

Ablation efficiency improvement

B. Jaeggi et al., "Influence of the pulse duration in the ps-regime on the ablation efficiency of metals,"Physics Procedia, vol. 12, pp. 164-171, 2011.

- **efficiency can be increased by reducing the pulse duration**
- **in picosecond regime**, ablation **efficiency for metals can be improved *n* times**
- through the increase of threshold fluence
- pulse duration is reduced n-time

but…

Ablation efficiency improvement

- reduction of pulse length to **femtosecond** regime can increase ablation efficiency
- achieved mainly **not** through the threshold fluence
- Achieved for **improvement of the energy penetration depth *δ***

B. Neuenschwander, B. Jaeggi, M. Schmid, U. Hunziker, B. Luescher, C. Nocera, "Processing of industrially relevant nonmetals with laser pulses in the range between 10 ps and 50 ps," In Proc. of ICALEO 2011, paper M103, 2011.

- in ***soft materials*** with low conductivity, ablation is fine even for relatively long pulse

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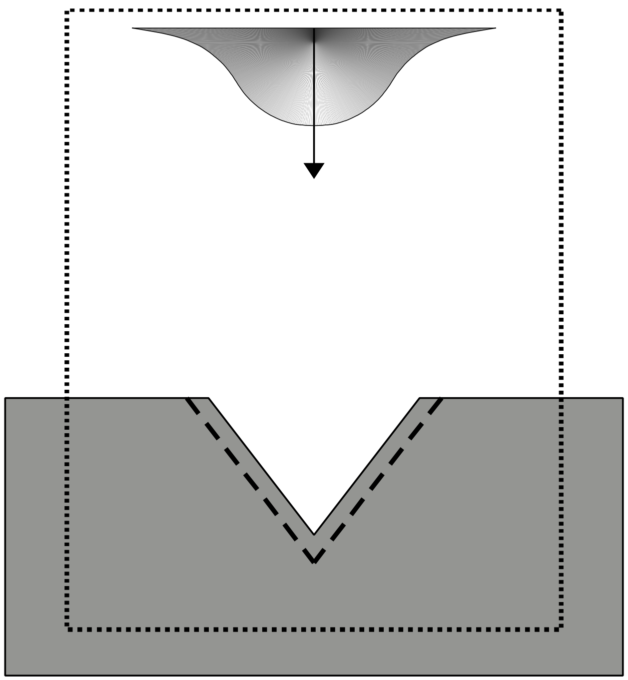
Modeled V-groove



2D model, energy is propagated along *y* axis

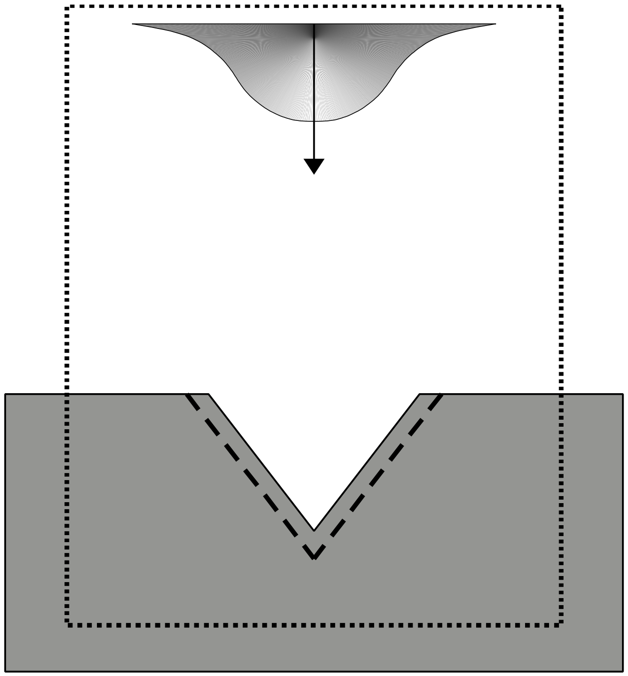
My first ”but” was…

- *laser pulse properties can be* ***getting different****, as the pulse is* ***propagated*** *in the V-groove*
- beam is incident on iron plate and its interaction with the metal plate

- shape of groove considered for simulations resembles letter *V*

K. H. Laitz, B. Redlingshoefer, Y. Reg, A. Otto, M. Schmidt, “Metal ablation with short and ultrashort laser pulses,” Physics Procedia, vol. 12, pp. 230-238, 2011.

Laser's parameters



2D model, energy is propagated along *y* axis

- Gaussian spatial distribution laser
- 300 fs pulses
- repetition rate *f* of 50 kHz
- average output power P_{avg} 5 W
- 8 nm full width half maximum (FWHM)
- output spectrum centered at 1040 nm

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Assumptions

- **energy penetration depth *δ*** is considered as the depth at which the power of the optical pulse in its center **decays to 1/e of its surface value**
- duration of the optical pulse is of the order of hundredths of ns, heat propagation effects can be neglected
- absorption is the main mechanism of attenuation in the iron

J. Byskov-Nielsen, "Short-pulse laser ablation of metals: fundamentals and applications for micro-mechanical interlocking," Doctoral thesis, Dept. Physics and Astronomy, Univ. of Aarhus, Aarhus, Denmark, 2010.

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Model of propagation

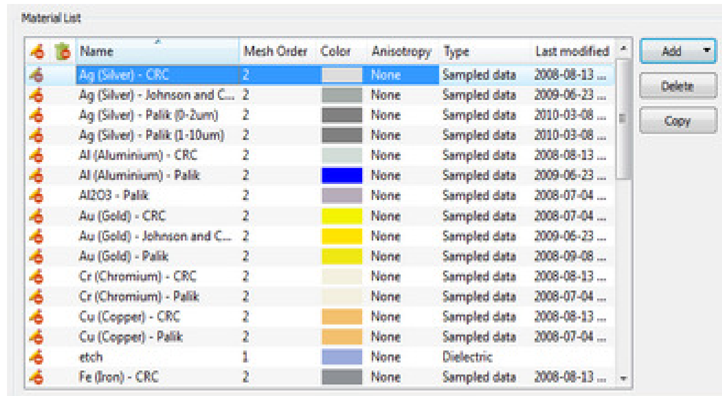
$$E_p = P_{avg} / f$$

$$\phi_0 = \frac{2E_p}{\pi w^2}$$

- Energy carried by a single pulse E_p can be calculated based on the average power P_{awg} and repetition rate f of the source
- the incidence size of the beam on the iron plate is specified as a spot **size radius *w***
- Based on the pulse energy, one can subsequently yield the peak fluence ϕ_0, which is located for the considered Gaussian beam in its center
- the peak fluence was 44 W/cm^2

Simulation technique

- Material properties of the iron plate using **complex index of refraction** based on the measured data
- **polynomial** approximation applied to the data


Material List

Name	Mesh Order	Color	Anisotropy	Type	Last modified
Ag (Silver) - CRC	2		None	Sampled data	2008-08-13 ...
Ag (Silver) - Johnson and C...	2		None	Sampled data	2009-06-23 ...
Ag (Silver) - Palik (0-2um)	2		None	Sampled data	2010-03-08 ...
Ag (Silver) - Palik (1-10um)	2		None	Sampled data	2010-03-08 ...
Al (Aluminium) - CRC	2		None	Sampled data	2008-08-13 ...
Al (Aluminium) - Palik	2		None	Sampled data	2009-06-23 ...
Al2O3 - Palik	2		None	Sampled data	2008-07-04 ...
Au (Gold) - CRC	2		None	Sampled data	2008-07-04 ...
Au (Gold) - Johnson and C...	2		None	Sampled data	2009-06-23 ...
Au (Gold) - Palik	2		None	Sampled data	2008-09-08 ...
Cr (Chromium) - CRC	2		None	Sampled data	2008-08-13 ...
Cr (Chromium) - Palik	2		None	Sampled data	2008-07-04 ...
Cu (Copper) - CRC	2		None	Sampled data	2008-08-13 ...
Cu (Copper) - Palik	2		None	Sampled data	2008-07-04 ...
etch	1		None	Dielectric	
Fe (Iron) - CRC	2		None	Sampled data	2008-08-13 ...

Add
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http://docs.lumerical.com/en/materials_default_optical_database.html

D. W. Lynch, W. R. Hunter, "An Introduction to the Data for Several Metals," in Handbook of Optical Constants of Solids, 1st ed., vol. 2, E. Palik, Ed. San Diego: Academic Press, 1997.

Simulation technique

- numerical electromagnetic solver employing a modified variational finite difference time domain (**FDTD**)

http://docs.lumerical.com/en/solvers_finite_difference_time_domain.html

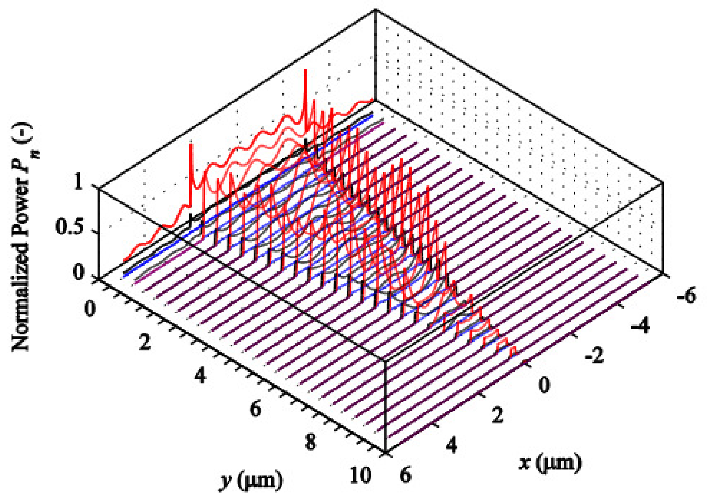
M. Hammer and O. V. Ivanova, "Effective index approximation of photonic crystal slabs: a 2-to-1-D assessment,"Optical and Quantum Electronics, vol. 42, no. 4, pp. 267-283, Dec. 2009.

- simulation region is divided into smaller **non-uniform computational cells** by meshing algorithm. Non-uniformity of cell size guarantees higher accuracy

https://www.lumerical.com/solutions/innovation/fdtd_conformal_mesh_whitepaper.html

W. Yu and R. Mittra, "A conformal finite difference time domain technique for modeling curved dielectric surface," IEEE Microwave and Wireless Components Letters, vol. 11, no. 1, pp. 25-27, 2001.

Results - pulse duration influence on propagation

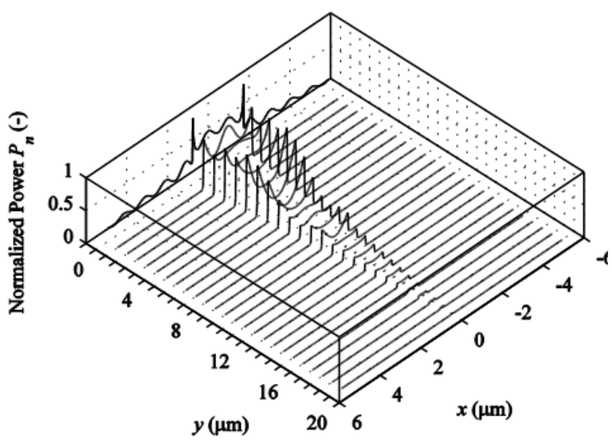


Propagation of a laser pulse in a V-groove.
Red – 100 fs, black – 300 fs, blue – 600 fs

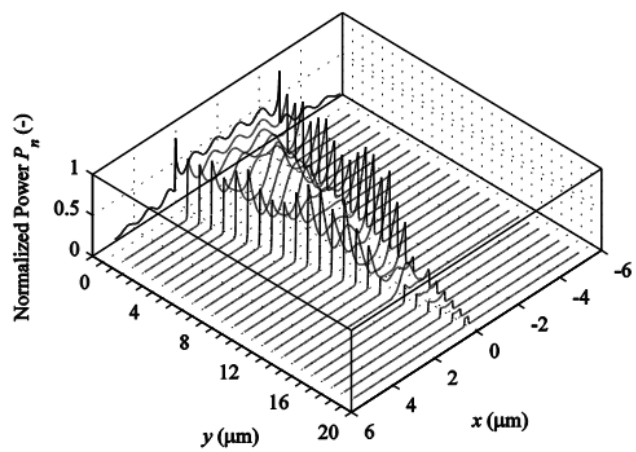
- V-groove width is 10 μm
- its depth 10 μm
- shortening the laser pulse duration from 600 fs to 100 fs shows greater penetration depth

- **in femtosecond regime greater efficiency is achieved through improved penetration depth**

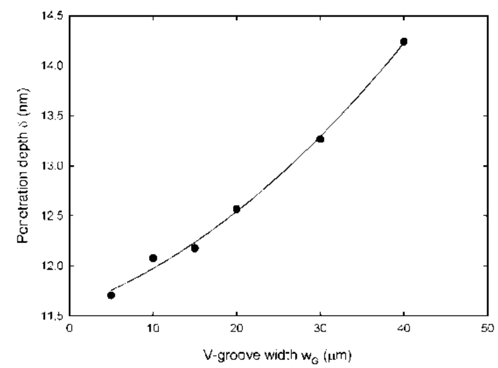
Results - groove **width** influence on propagation



Propagation in a V-groove with width 2.5 µm and depth 20 µm



Propagation in a V-groove with width 5 µm and depth 20 µm



Penetration depth vs. V-groove width

- V-groove depth fixed at 20 µm
- varied groove depth influences penetration depth
- changing the V-groove width affects the incidence of the beam on the sidewalls
- reflected radiation can interfere with the incident radiation
- near-linear dependence is observed

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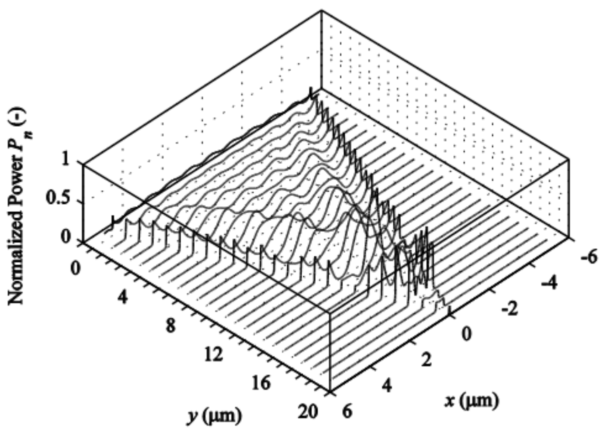
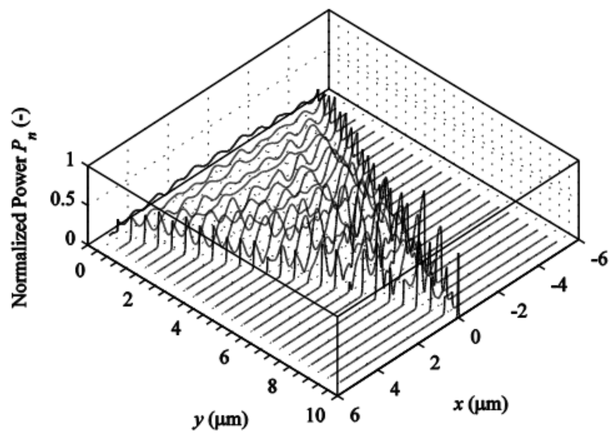
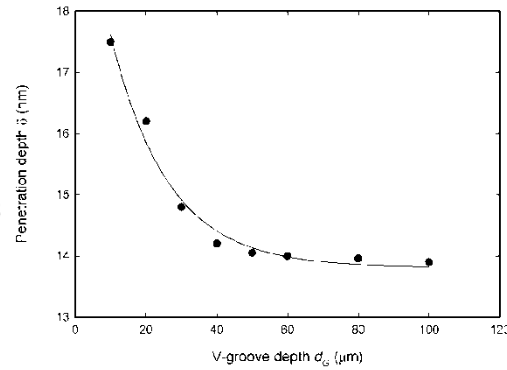
Results - groove **depth** influence on propagation



Propagation in a V-groove with width 10 µm and depth 20 µm



Propagation in a V-groove with width 10 µm and depth 10 µm



Penetration depth as a function of the depth of V-groove

- penetration depth decreases with higher **depth** of V-groove
- higher reflection of the beam from the sidewalls of the V-groove
- the higher depth, the greater is angle of incidence of the beam on the sidewalls
- **interference** with reflected light observed
- simulation data fits **exponential** decay

Conclusion

- **energy** transfer, as according to Neunschwander model, is the main feature responsible for ablation
- **propagation** effects concerned when accurate ablation required
- fluence and energy penetration depth key features
- **penetration** depth major in femtosecond lasers
- **V-groove width and depth influence penetration depth**

El trabajo del futuro…

- *incubation effects, ablated volume of material, the balance between threshold fluence and penetration depth are neglected*

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Thank you for your attention

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Potential cooperation
Dr. Dana Seyringer
Dr. Johann Zehetner