Philipps Universität Marburg

Monitoring the plant water status with terahertz waves

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Experimentelle Halbleiterphysik
Arbeitsgruppe M. Koch

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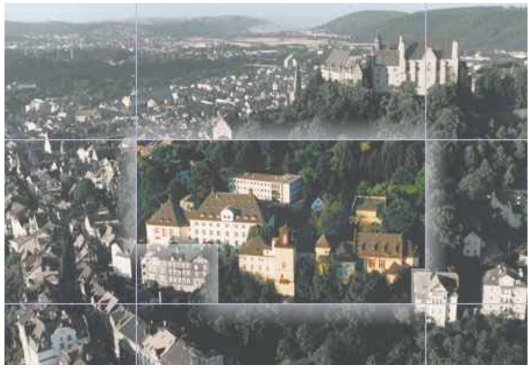


Experimentelle Halbleiterphysik
Arbeitsgruppe M. Koch

…(and several colleagues) at 4^{th} Terahertz workshop on Elba (2012)

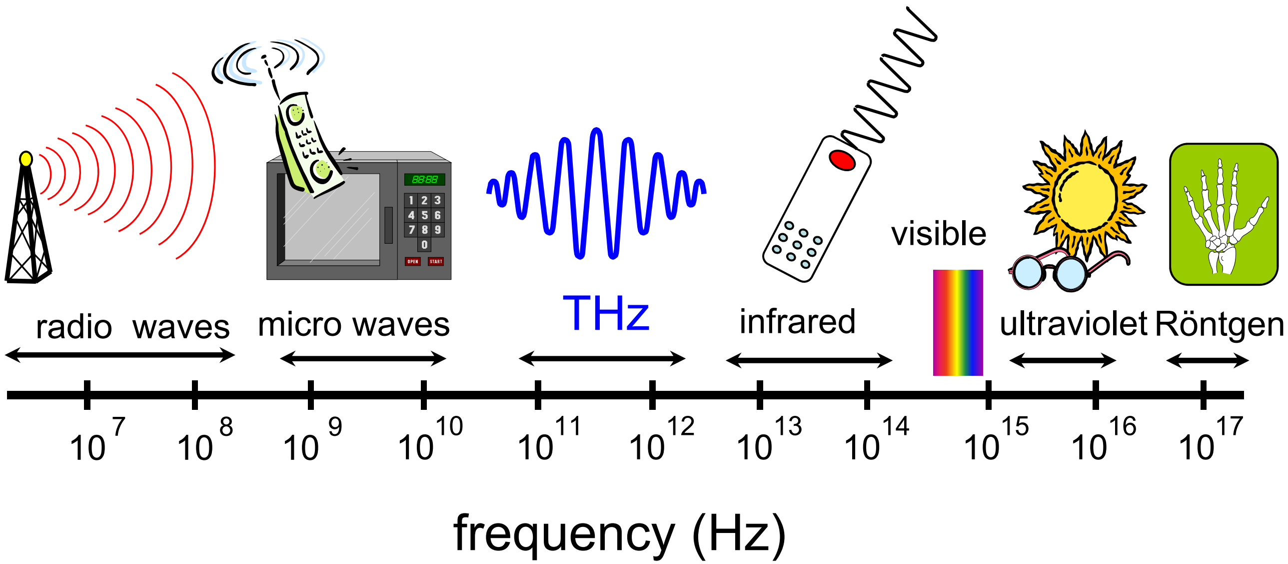
...thanx

Experimentelle Halbleiterphysik
Arbeitsgruppe M. Koch

main topics of interest

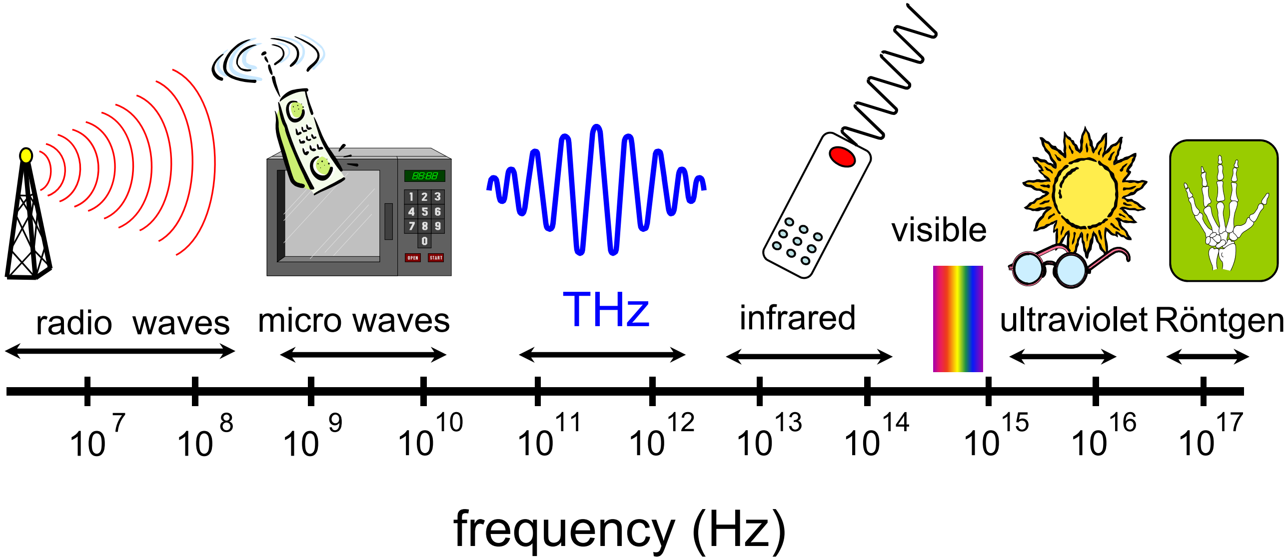
- ultrafast spectroscopy of semiconductor nanostructures
- development of semiconductor disk lasers
- terahertz systems and their applications

Electromagnetic TeraHertz (THz) radiation



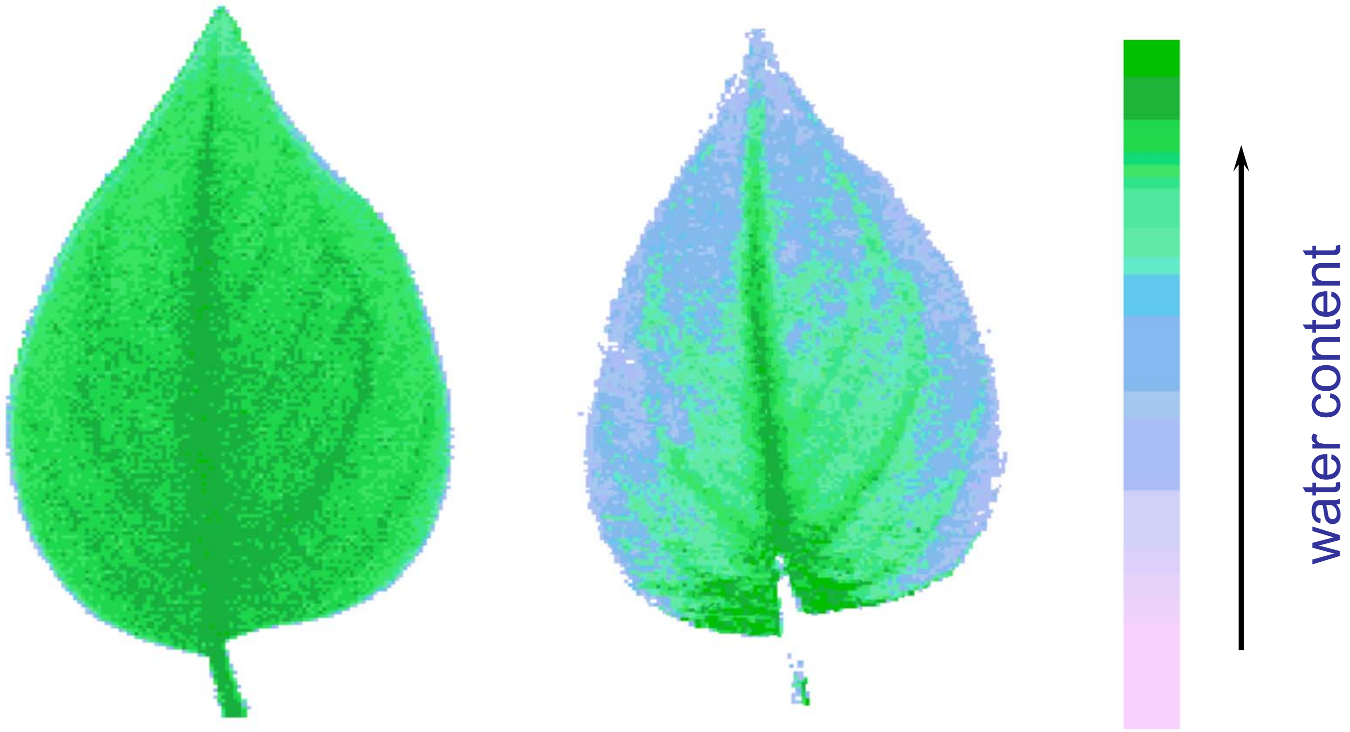
high frequency microwaves ← THz → extreme far infrared light

Electromagnetic THz radiation



frequency	0.1 THz	-	10 THz
photon energy	0.4 meV	-	41 meV
wavelength	3000 µm	-	30 µm
wavenumber	3.3 cm^{-1}	-	333 cm^{-1}

First demonstration of imaging THz spectroscopy



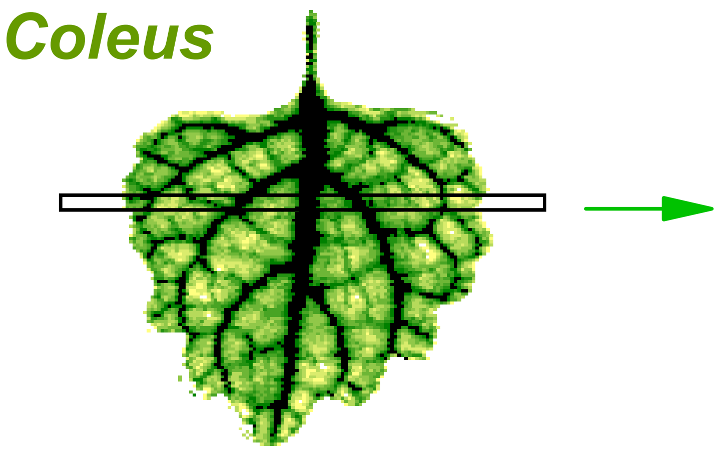
fresh leave

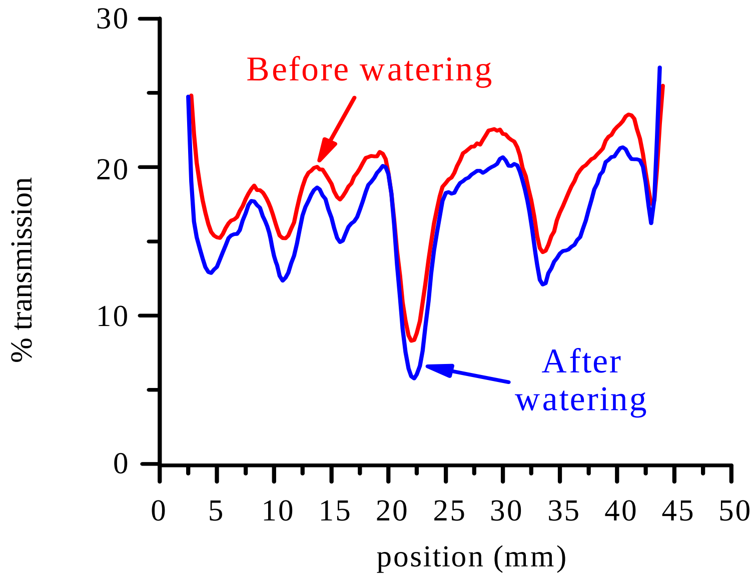
48 h after cutting
the leave

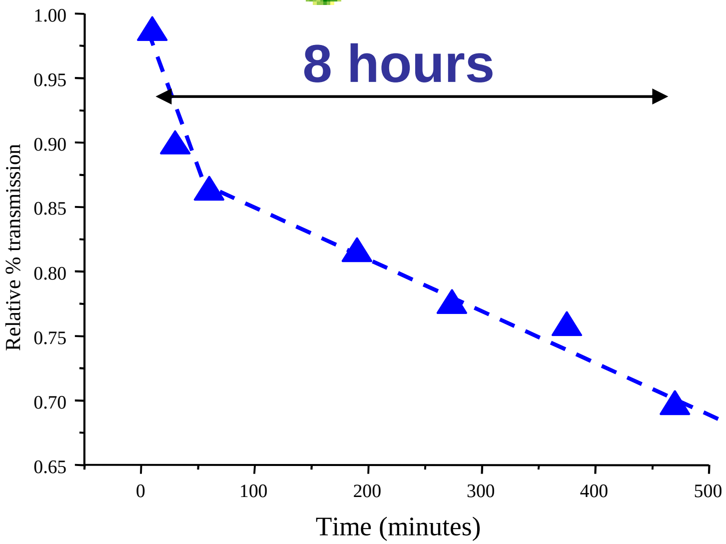
Bell Labs
Lucent Technologies

B.B. Hu and M.C. Nuss, Opt. Lett. 20(1995)1716

First THz monitoring of rehydration



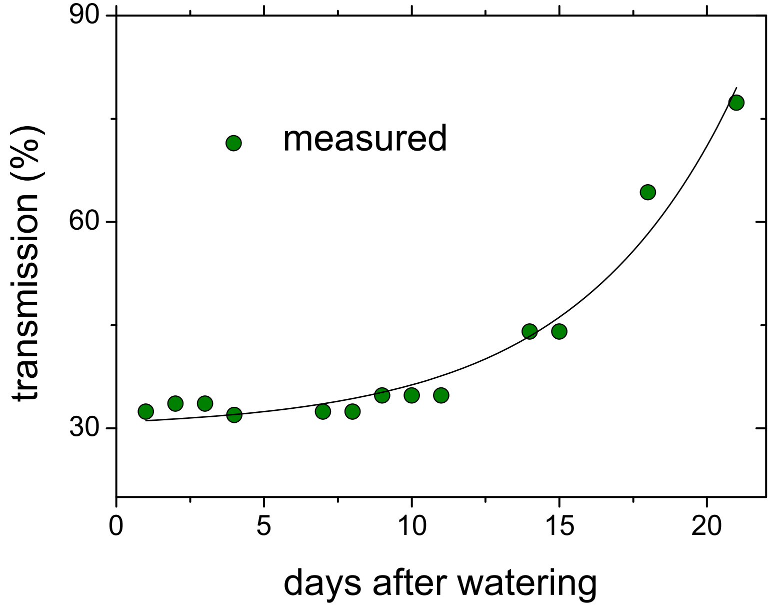


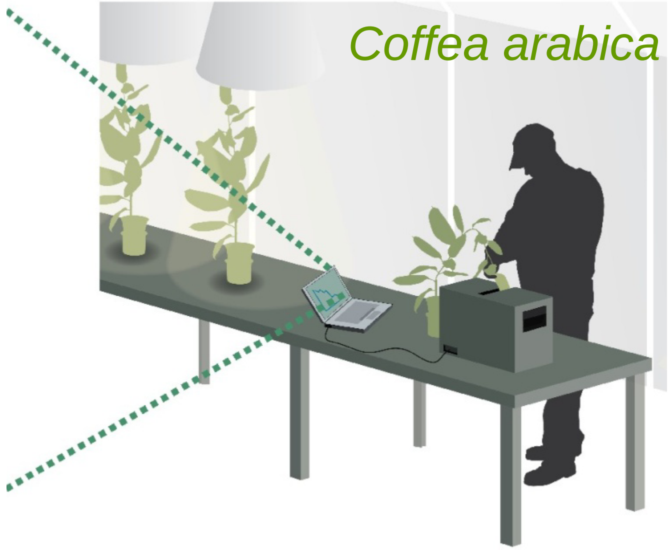


Bell Labs
Lucent Technologies

D. Mittleman et al., IEEE Journal of Selected Topics in Quantum Electronics 2(1996)679

Water status of plants





- THz transmission - close-to-real-time information about hydration and dry stress
- non-destructive
- water supply - intelligent irrigation strategies for plant breeding industry
- monitoring for selective cultivation

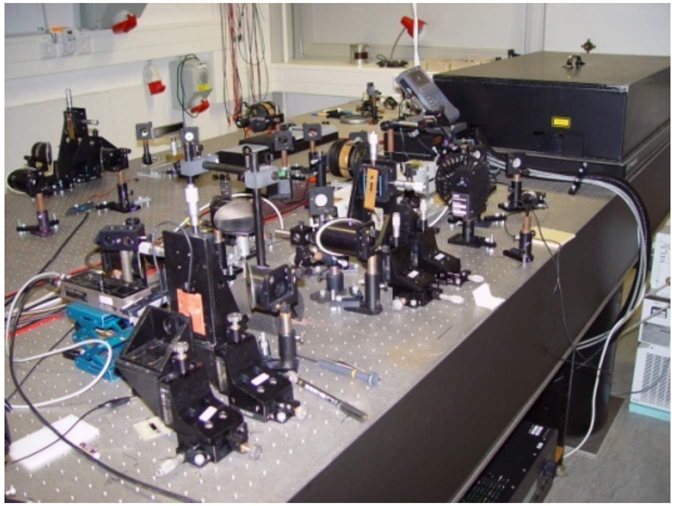
C. Jördens *et al.*
JBiologicalPhysics35(2009)255

…but not only in the lab

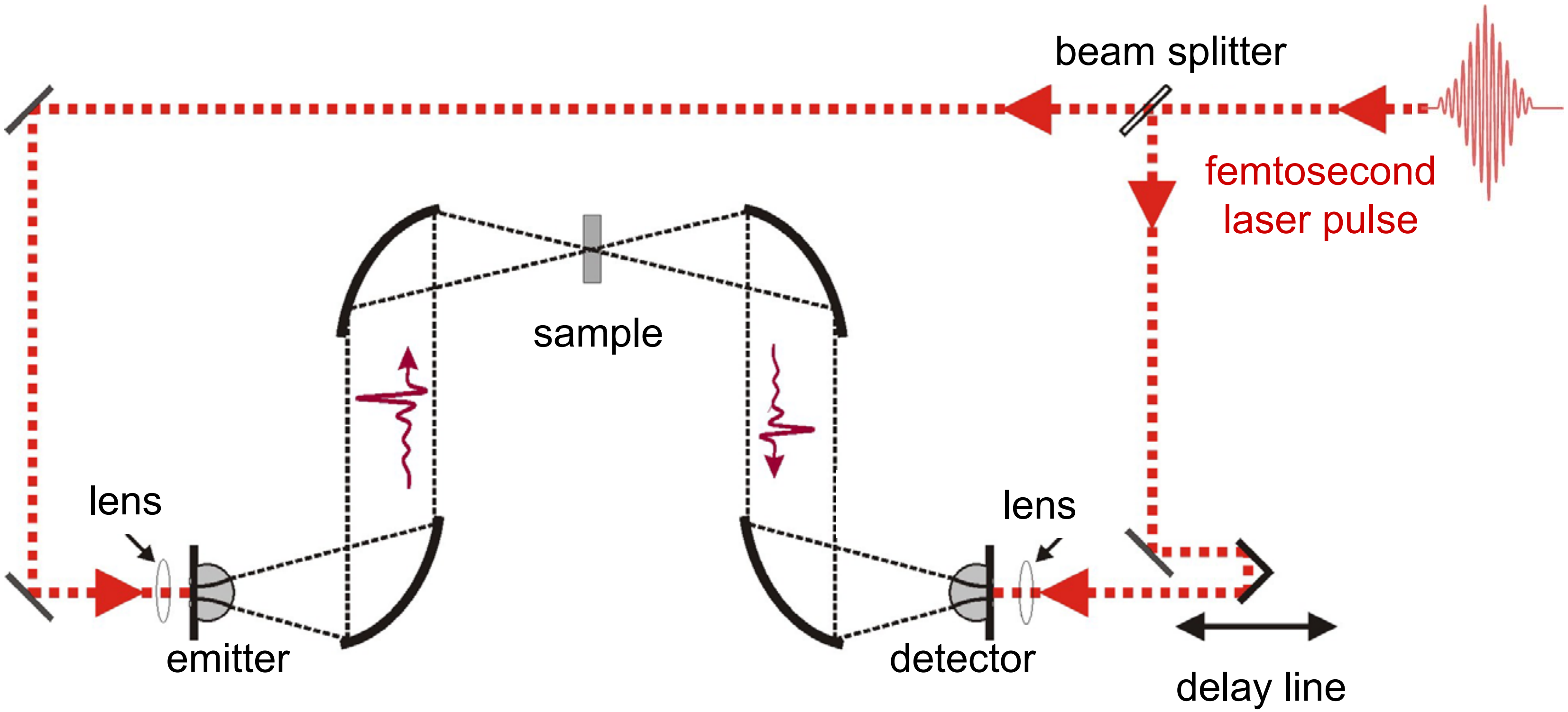
…plants live outside

Pulsed THz spectroscopy

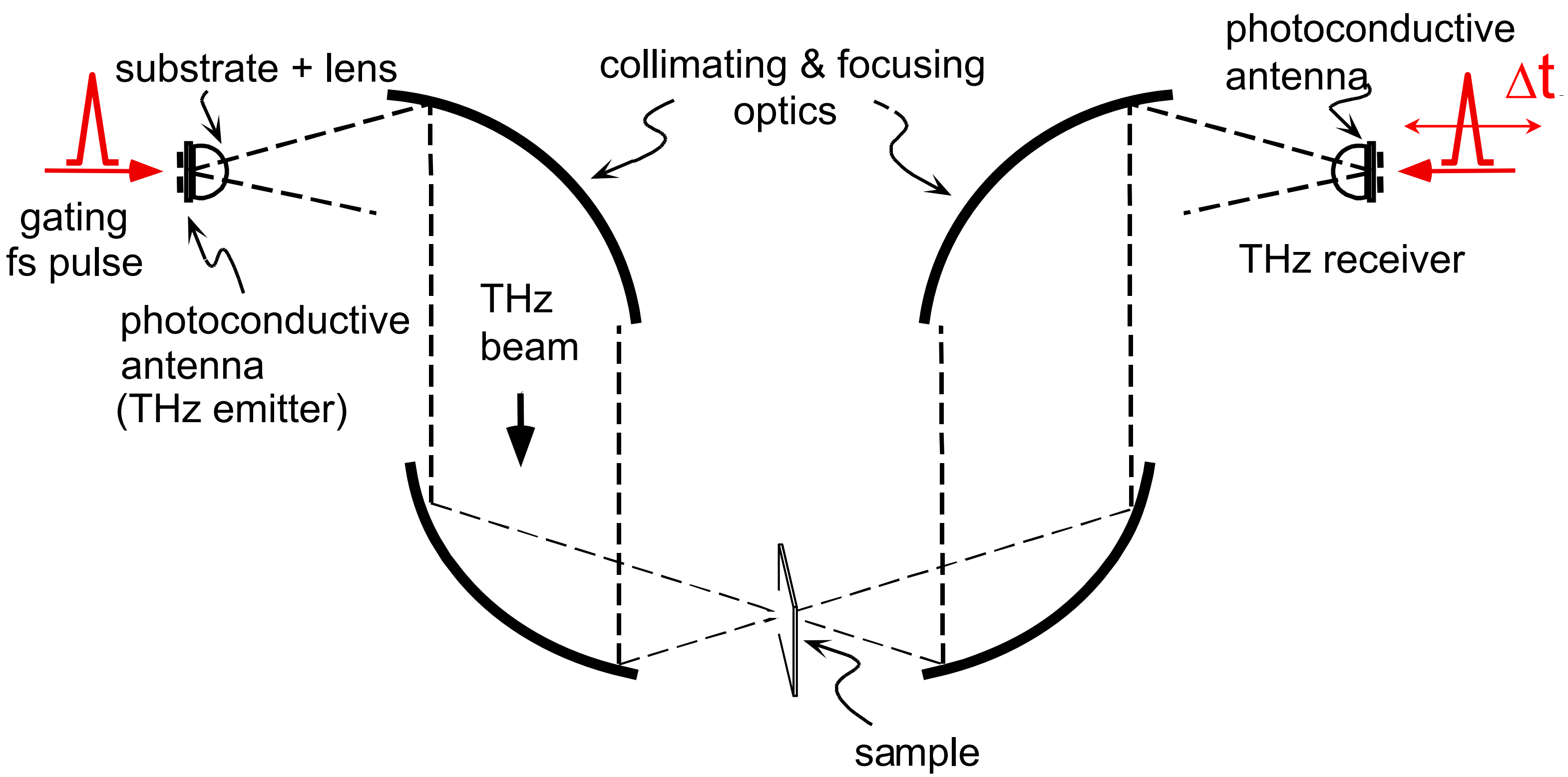
Laboratory setup



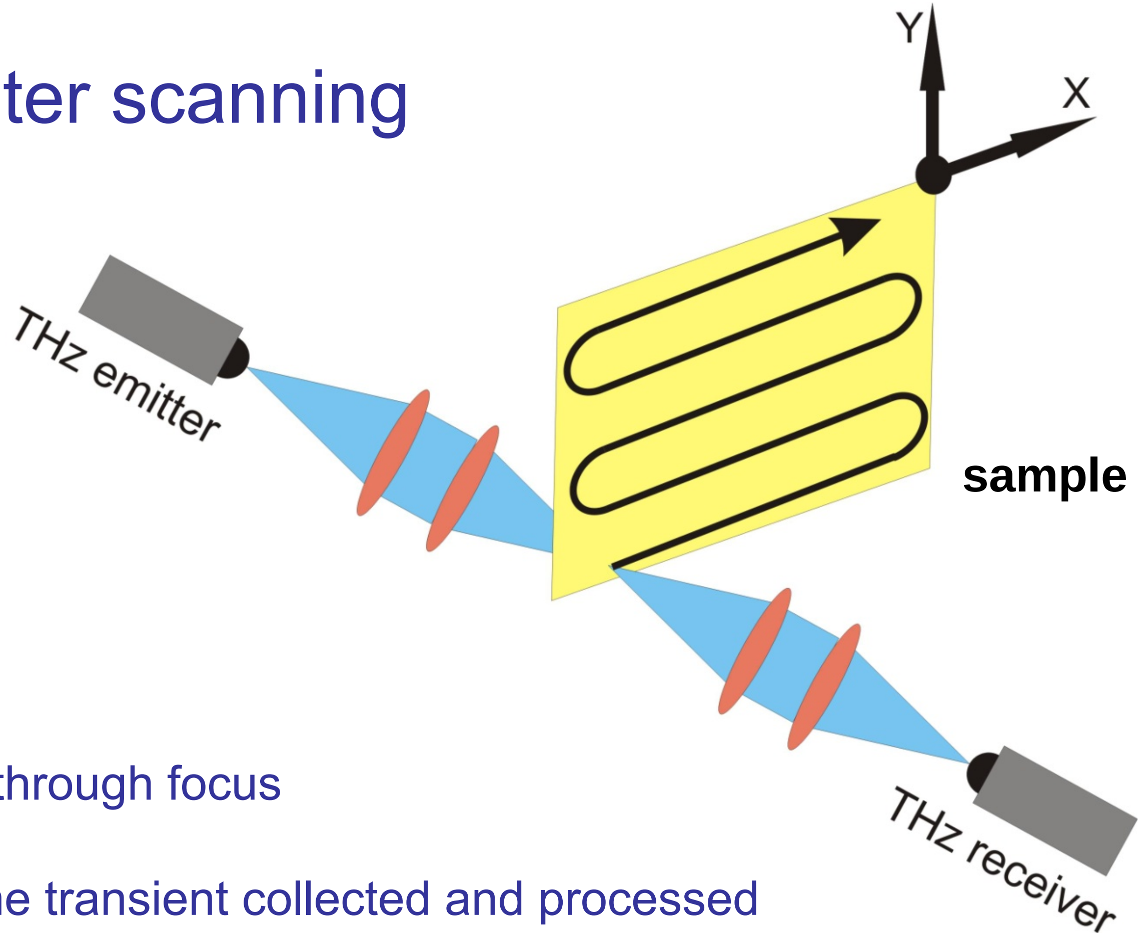
THz time domain spectroscopy
(THz TDS)



THz TDS spectrometer



Imaging - raster scanning



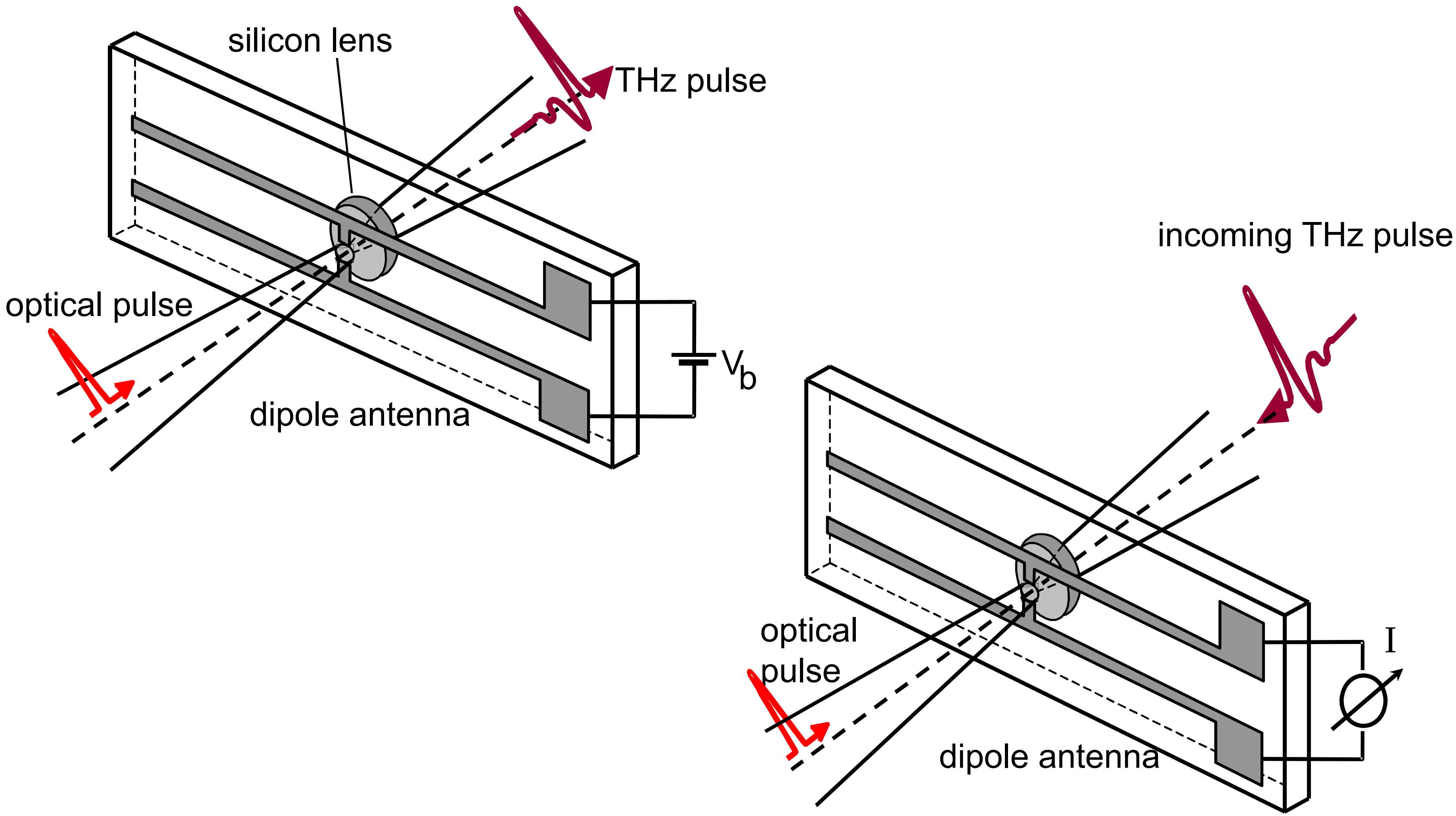
sample scanned through focus

for every pixel time transient collected and processed

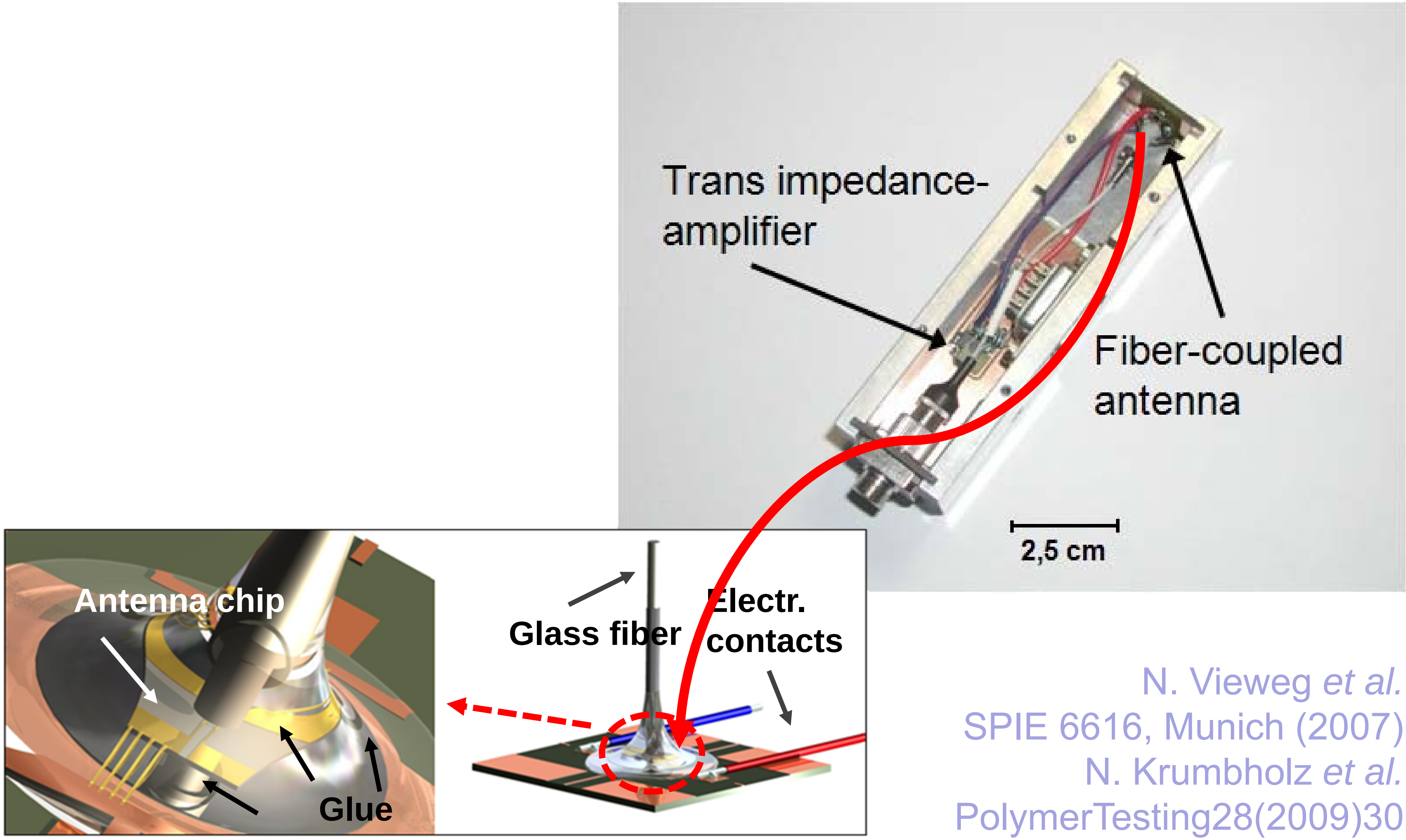
integrated transmission over frequency window gives image pixel value

…typically image takes some time

Emission and detection of THz pulses



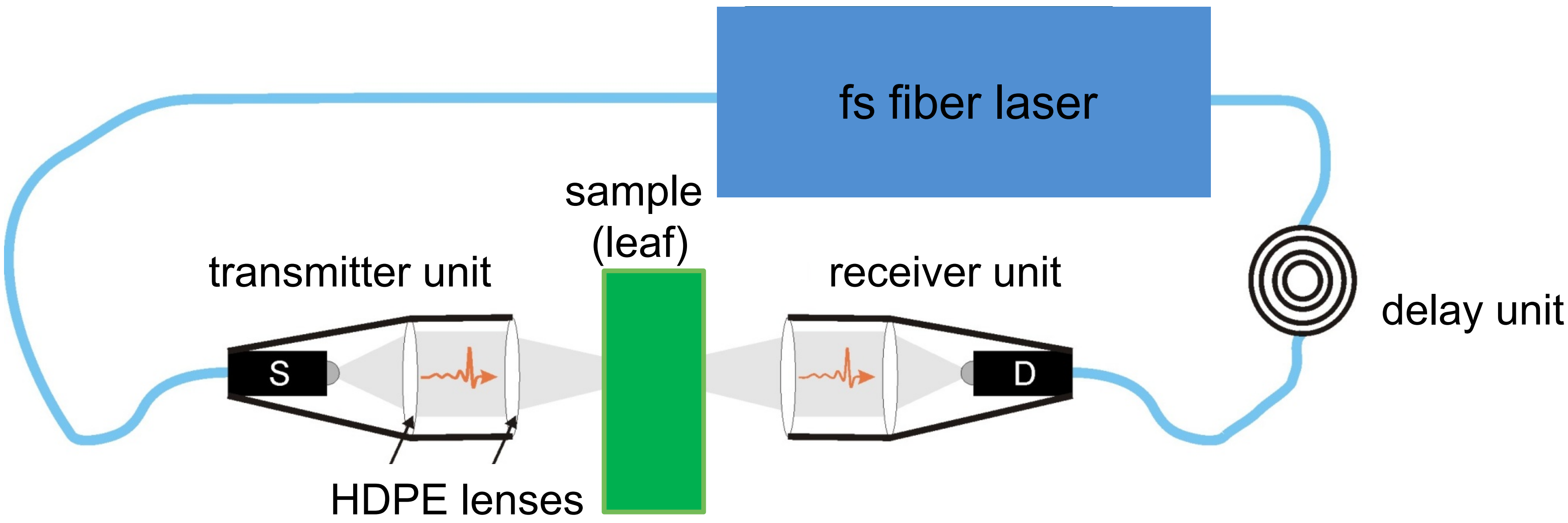
Fiber coupled THz antennas



N. Vieweg *et al.*
SPIE 6616, Munich (2007)
N. Krumbholz *et al.*
PolymerTesting28(2009)30

Harsh environment

…need for fiber based system



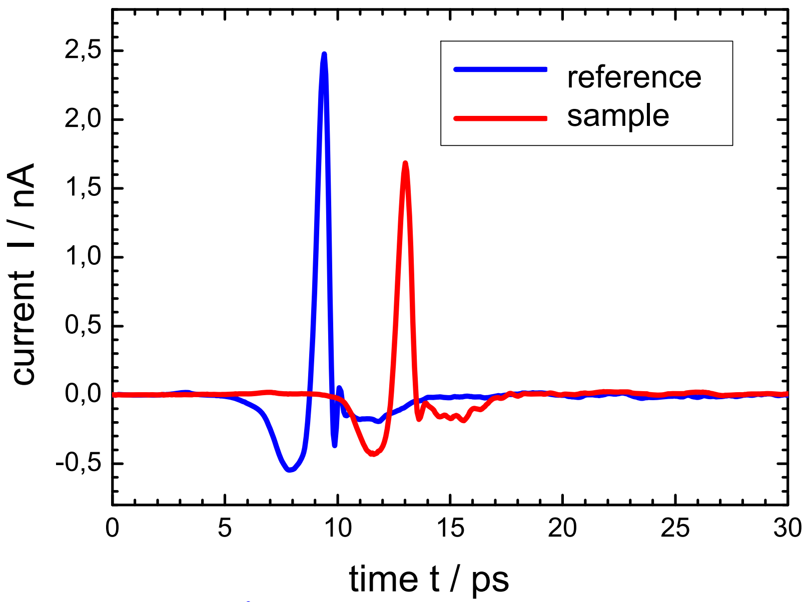
Signal processing

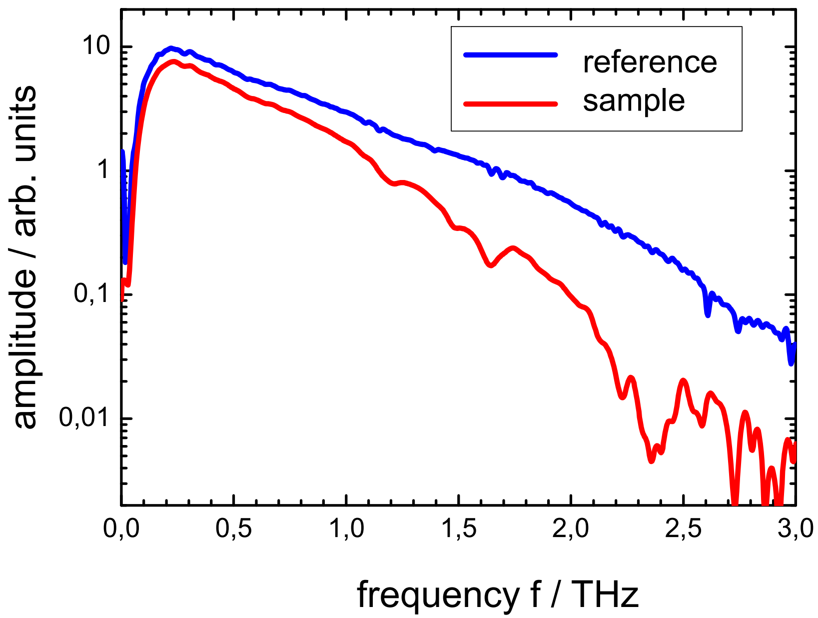
Signal processing → fundamental

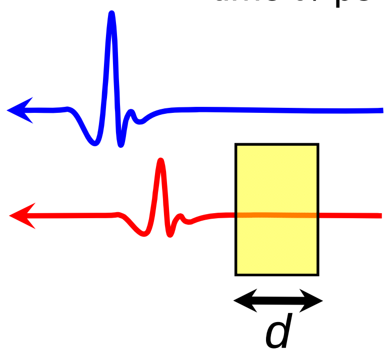
time domain (THz pulse)

FFT

frequency domain







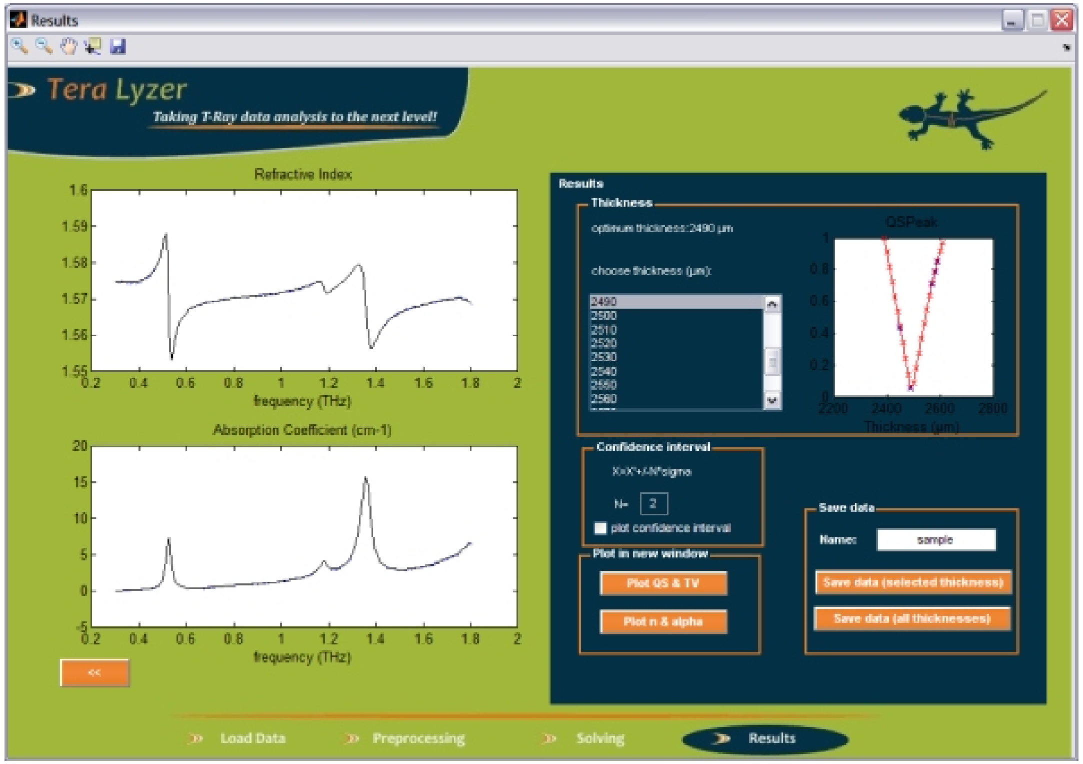
dielectric properties of sample

$$\underline{n} = n - i\kappa \qquad \kappa = \alpha \cdot c_0 / (4\pi\lambda)$$

phase difference ↔ **refractive index *n*(*f*)**

ratio of amplitudes ↔ **absorptions coefficient *α*(*f*)**

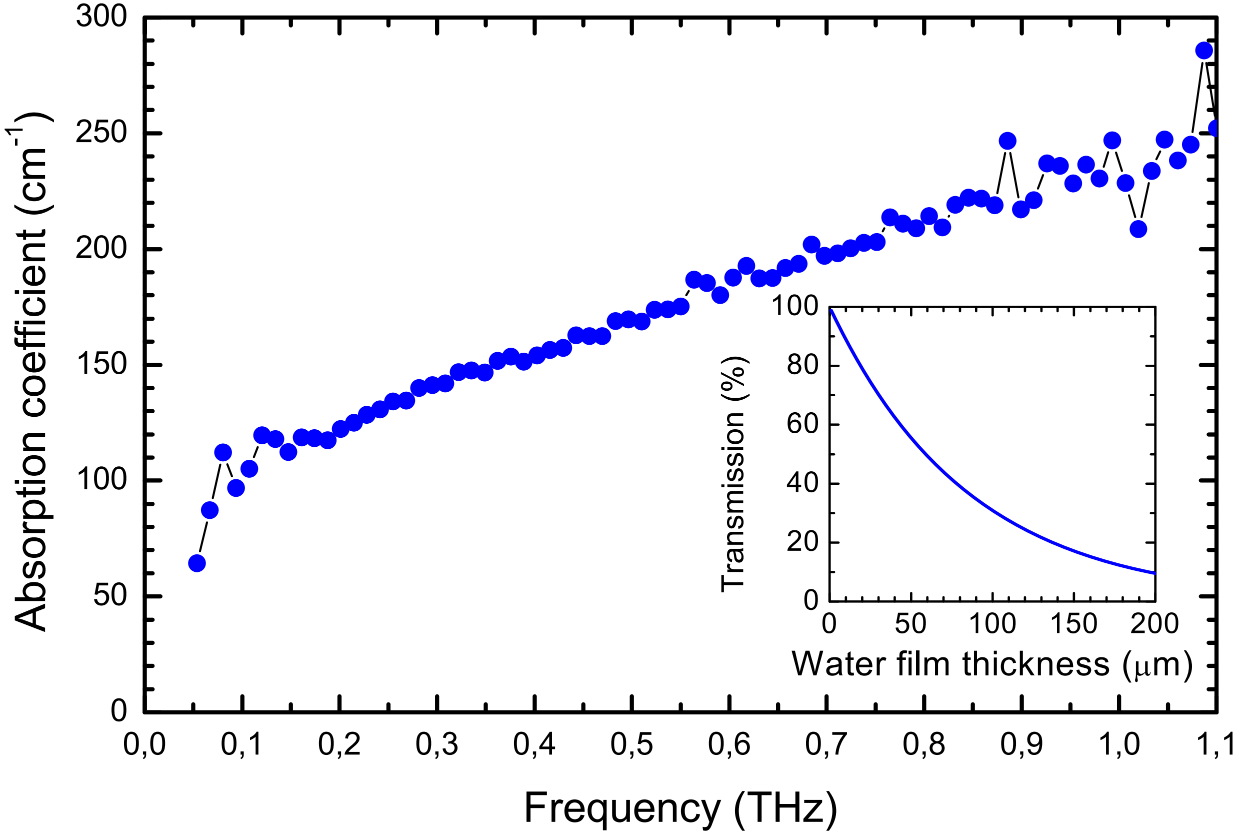
Signal processing - advanced



software commercially available…The *Tera Lyzer*

- simultaneous extraction of thickness and optical parameters
- multi-layer analysis possible
- versatile time preprocessing features

THz transmission through water film



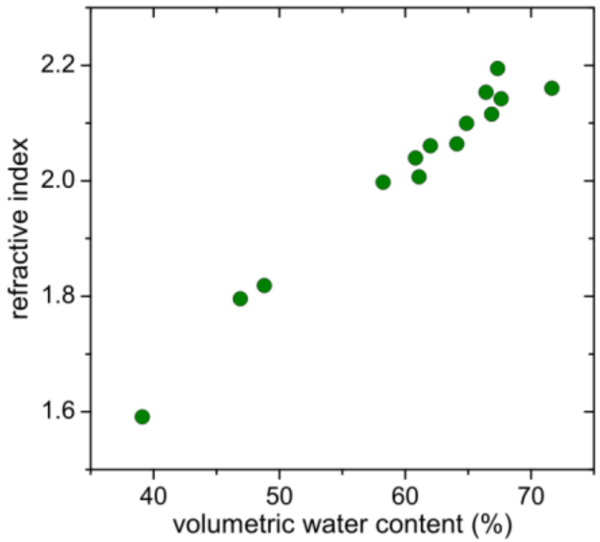
cannot penetrate water film thicker than few 100 µm

attenuation depends on frequency

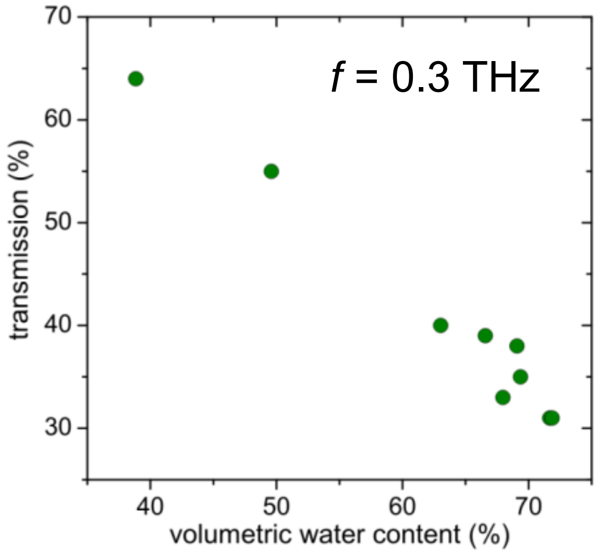
Monitoring the plant water status

Coffea arabica

refractive index



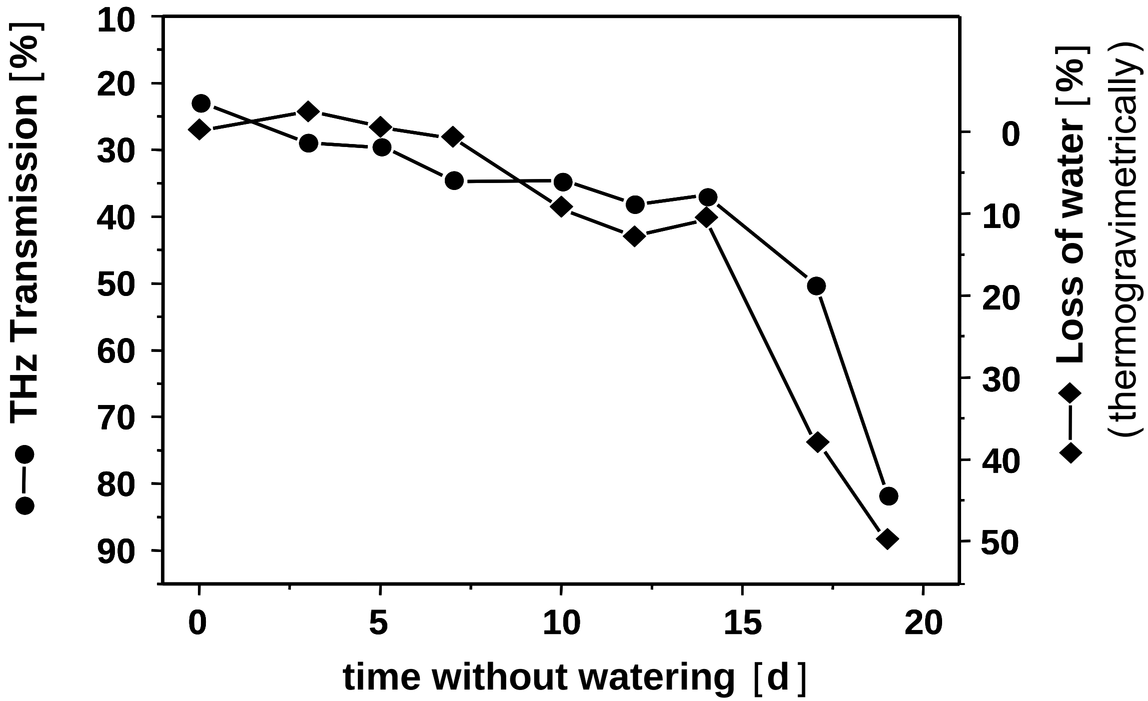
absorption



Monitoring the plant water status

…inside the lab - works well

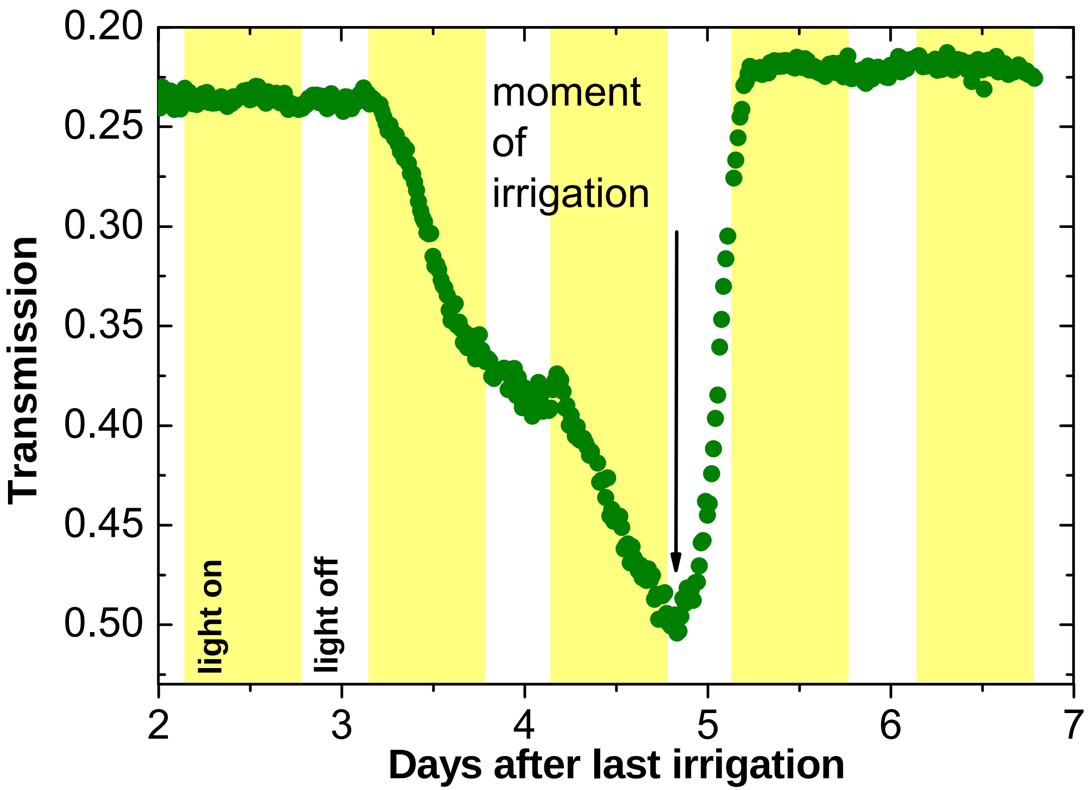
Coffea arabica



C. Jördens *et al.*
JBiologicalPhysics35(2009)255

Drought stress

…of oilseed rape (Brassica napus L.)



Water content analysis based on a physical model

leaf consists of

dry plant material + water + air

effective medium theory (EMT)

optical properties result from volume contents

+ thickness + surface scattering

C. Jördens *et al.*
JBiologicalPhysics35(2009)255

nonlinear optimization to get water content

Lets go outside the lab!

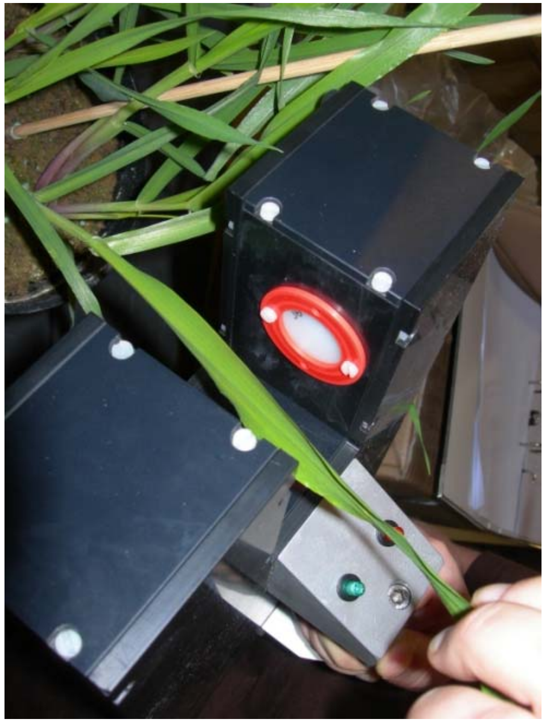
computer controlled

all fiber based

THz TDS spectrometer

inside rack

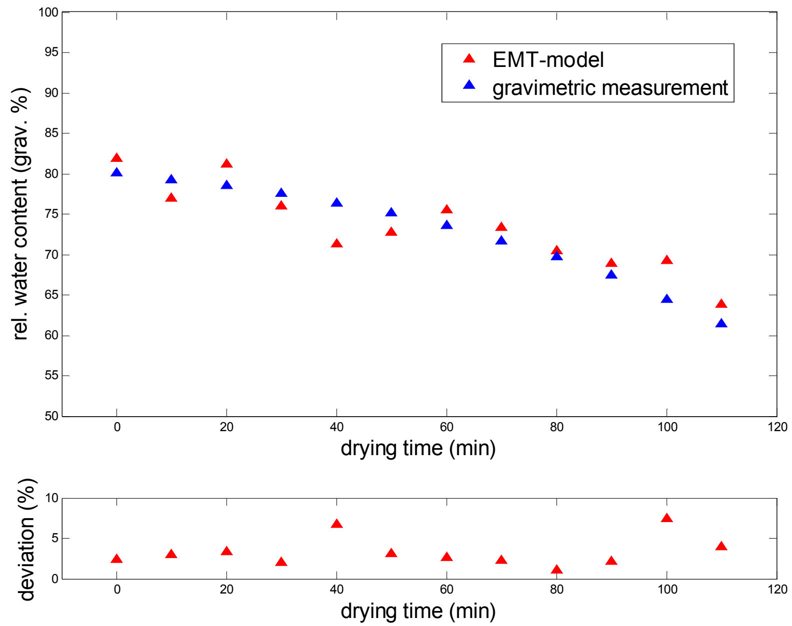
with handheld sensor head

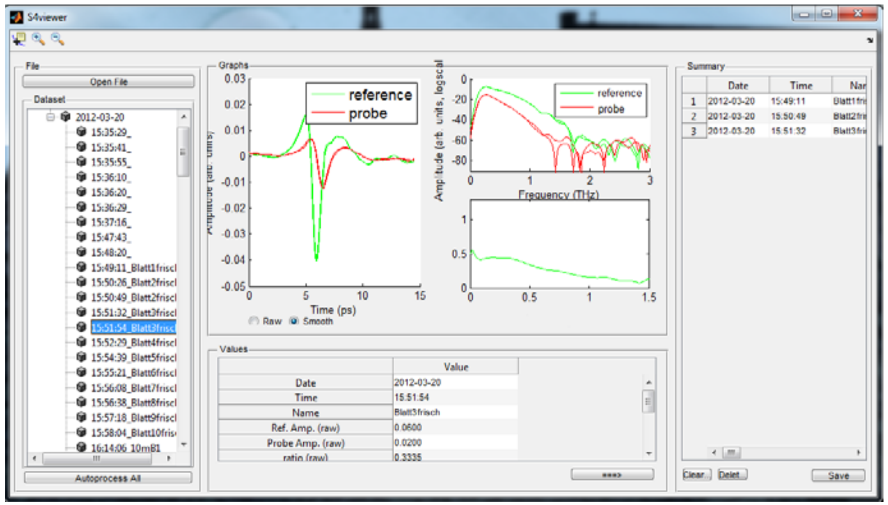


…outside the lab

…it works!

barley

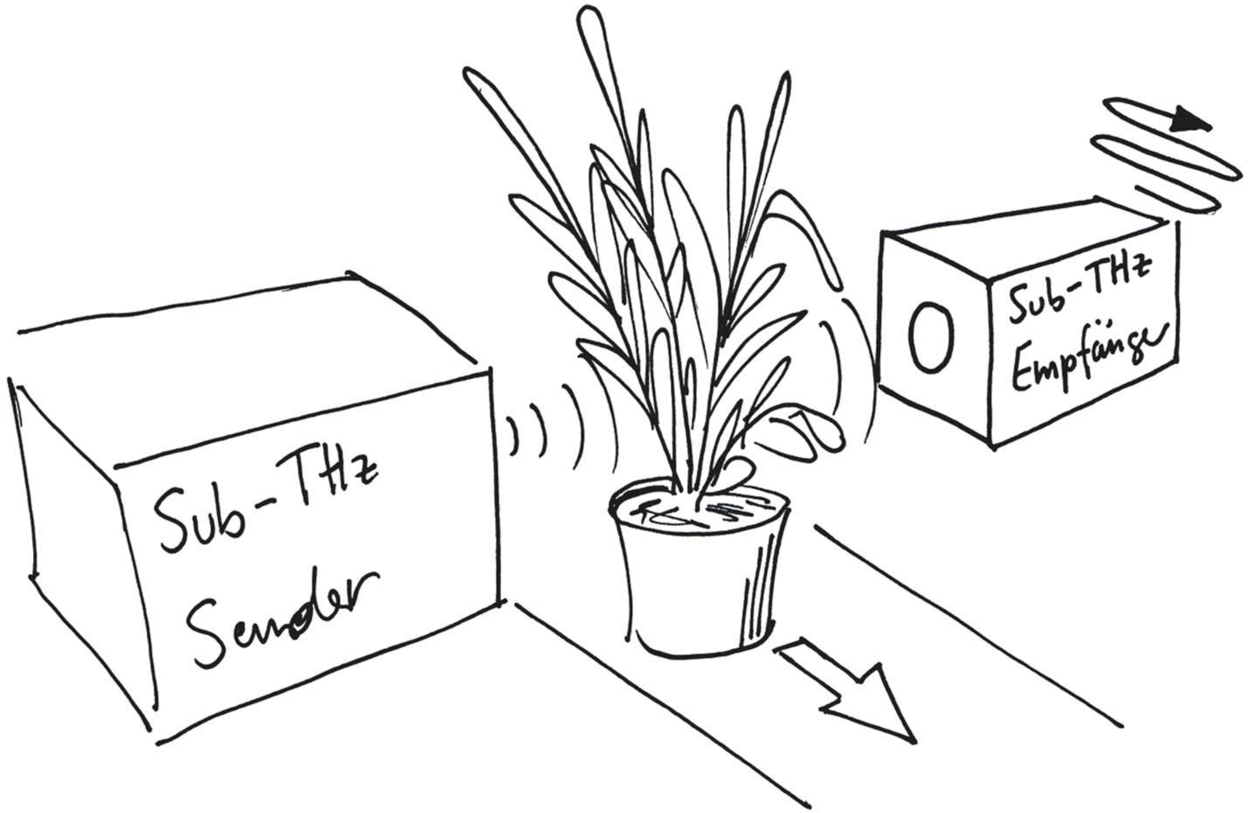




Application of a further system inside greenhouse

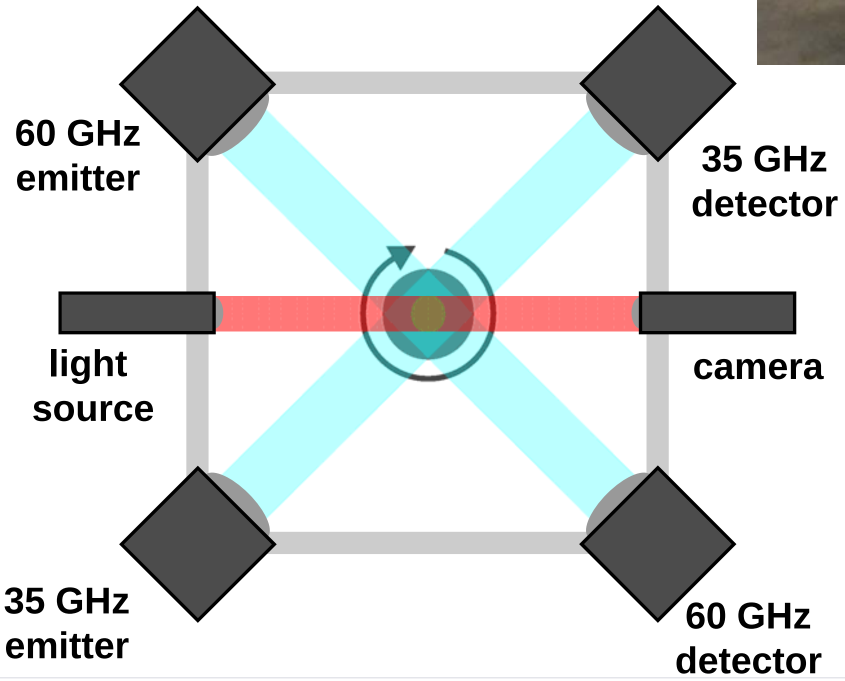
Sub-THz system

…the idea of the chef

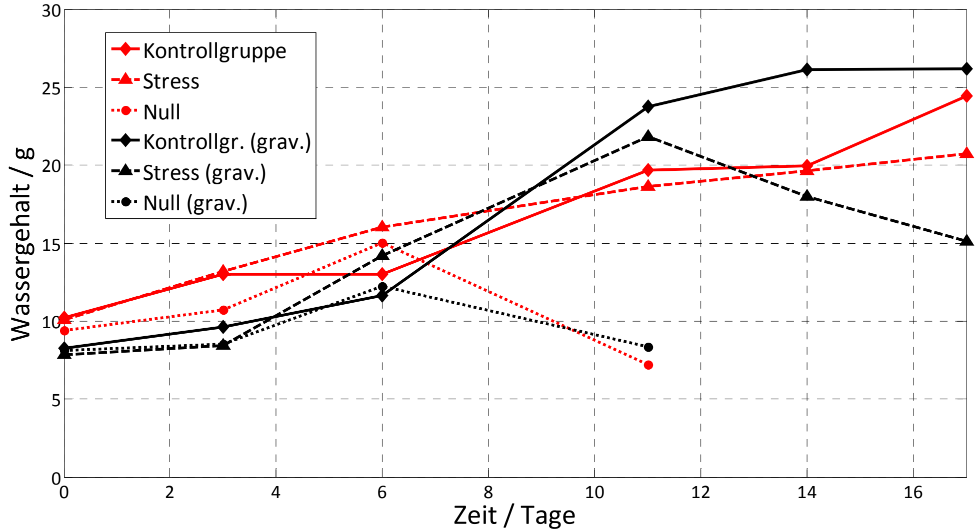


Sub-THz system

…and what comes out



Sub-THz system



water content of barley plants vs time
watered in different ways
red: sub-THz measurements
black: gravimetric measurements

Monitoring the plant water status with THz waves

- THz radiation senses through many opaque materials
- non-destructive and contactless sensing
- spatial resolution in the range of mm
- high sensitivity for water (inside plants)
- nearly ready for commercialization

Thank you for your attention!

Special thanks to Norman Born, Ralf Gente, Michael Schwerdtfeger, and Nino Voß