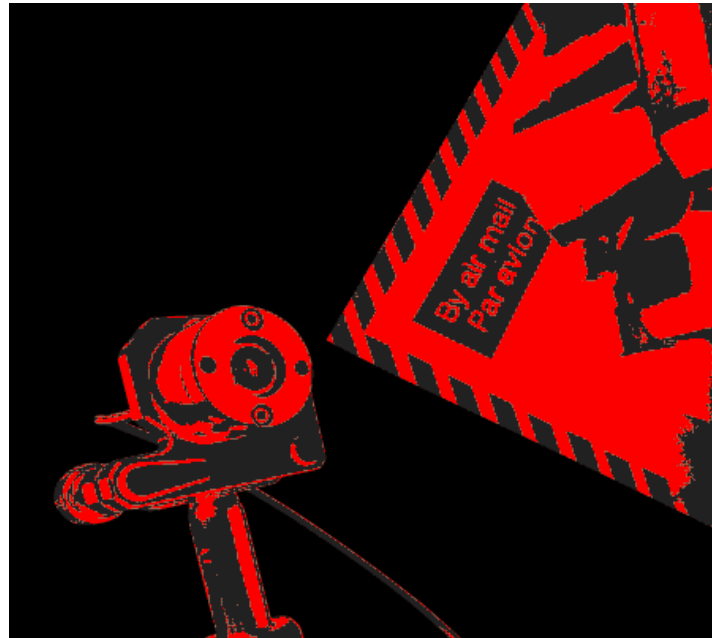


Terahertz Technologies for Industrial Applications



Dr. Anselm Deninger
TOPTICA Photonics AG

LOEWE STT Workshop – 11.04.2013

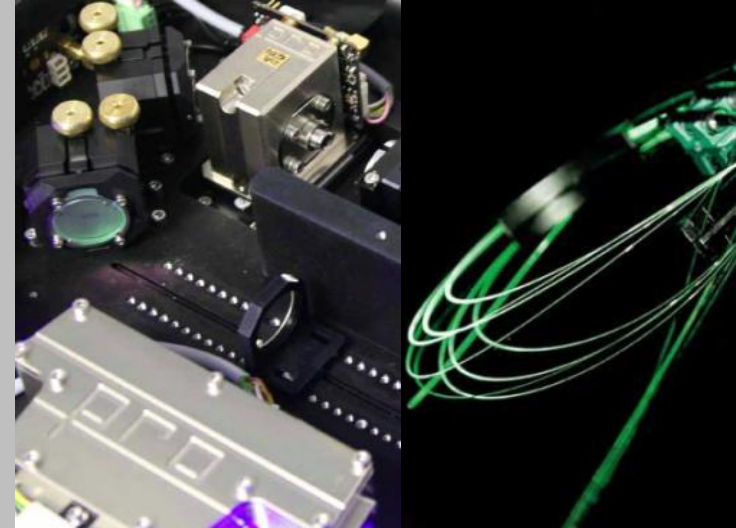
TOPTICA: Key Figures

Technology:

Diode Laser Systems 190 – 3500 nm

Ultrafast Fiber Lasers 485 – 2200 nm

Terahertz Generation 0 – 4 THz



Key Figures:

Employees: 140

Founded: 1998

Locations: Gräfelfing (Munich)
Victor (NY/USA)



Overview

▶ Terahertz Bubbles

▶ Time-Domain Terahertz

- ▷ Techniques and technology

▶ Frequency-Domain Terahertz

- ▷ Techniques and technology

▶ Application Examples

- ▷ Detection of toxic gases
- ▷ Measurement of paint layers on automobiles
- ▷ Paper humidity monitoring
- ▷ Terahertz imaging

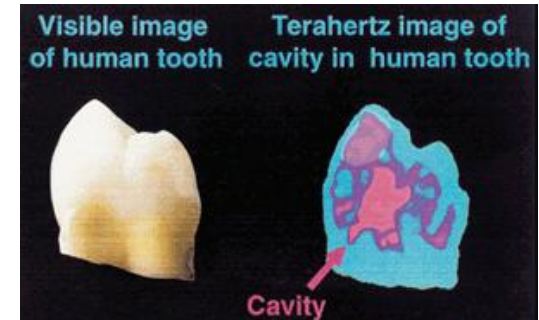
▶ Summary

Terahertz “Bubbles”

What Terahertz **cannot** do:

▶ Medical imaging

- ▶ Sub-millimeter penetration depth in tissue and teeth
- ▶ Published results obtained with exised, sliced samples



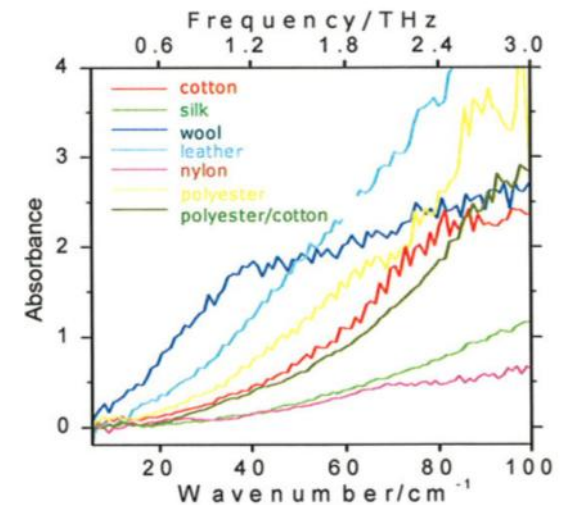
Source: TeraView Ltd.

▶ Stand-off detection of explosives (> 5 m)

- ▶ Absorption by water vapor limits working range
- ▶ Only “window frequencies” survive (300/600 GHz) – not relevant for explosives (1-3 THz)

▶ Identification of explosives beneath clothing

- ▶ Clothing materials are opaque above 1 THz
- ▶ Only nylon and silk transparent – little practical use



Terahertz Perspectives

What Terahertz **can** do:



- ▶ **Terahertz Bubbles**

- ▶ **Time-Domain Terahertz**

- ▷ Techniques and technology

- ▶ **Frequency-Domain Terahertz**

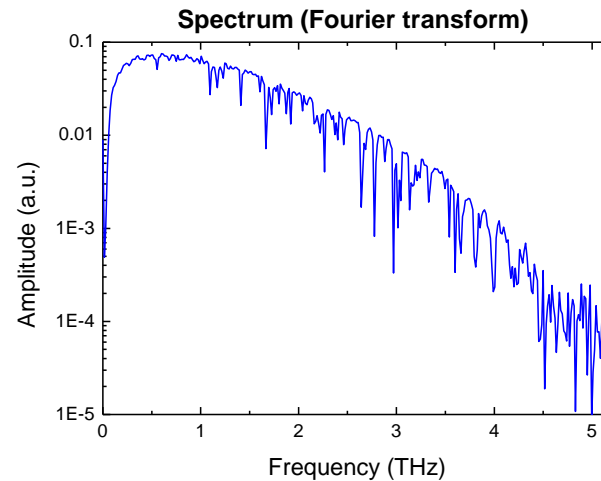
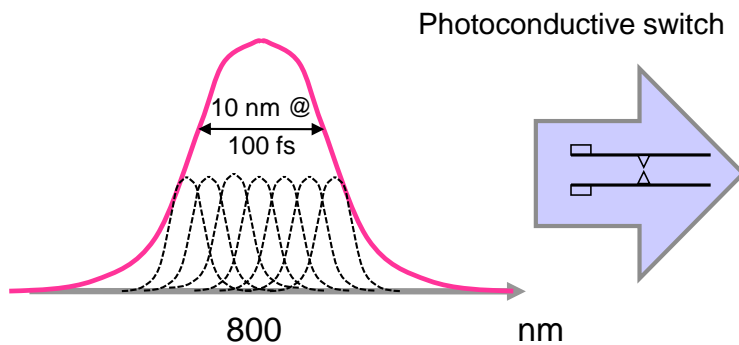
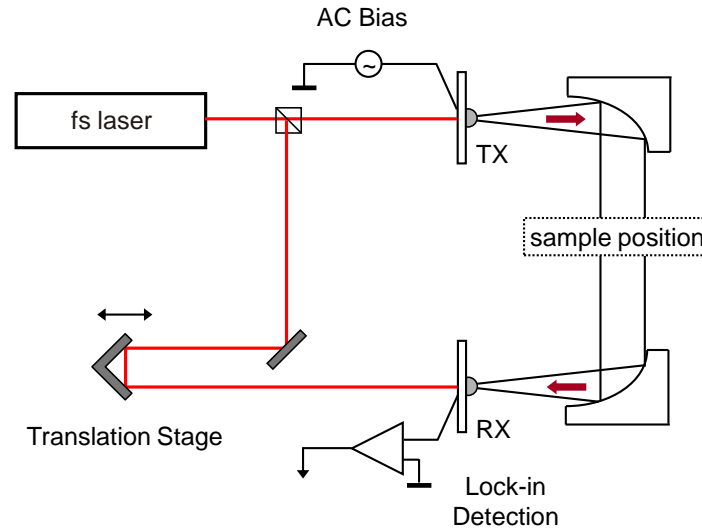
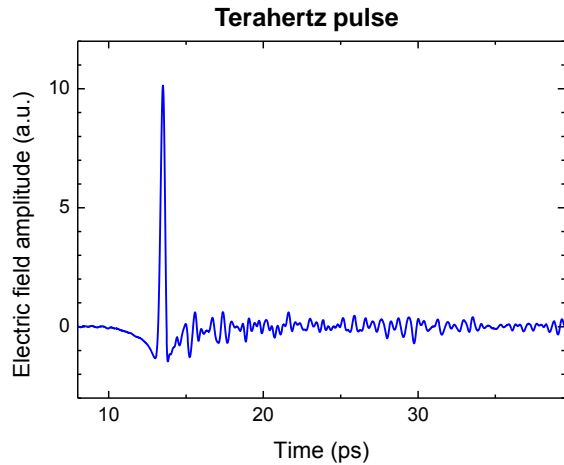
- ▷ Techniques and technology

- ▶ **Application Examples**

- ▷ Detection of toxic gases
- ▷ Measurement of paint layers on automobiles
- ▷ Paper humidity monitoring
- ▷ Terahertz imaging

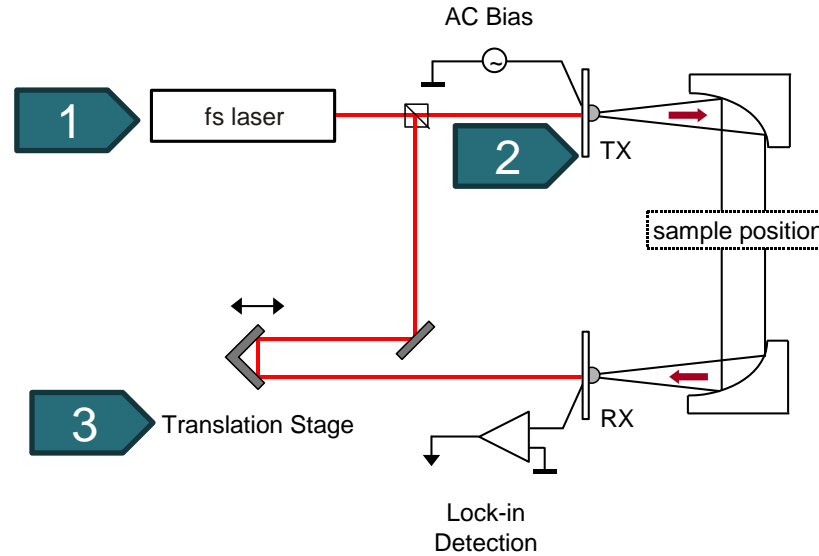
- ▶ **Summary**

Time-Domain Terahertz Generation



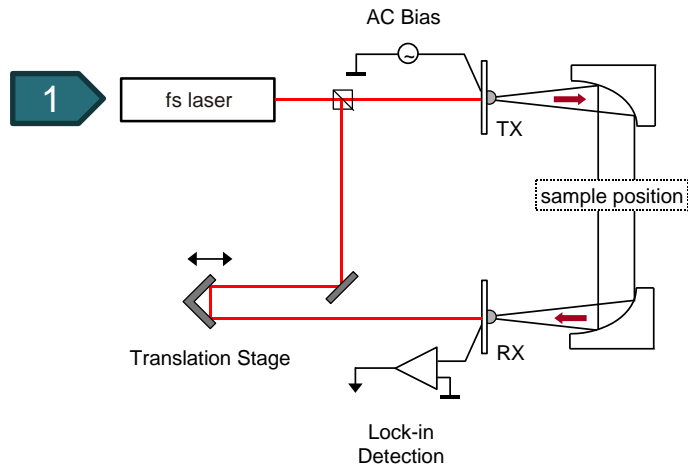
Bandwidth of THz spectrum: Spectral response of antenna x spectral width of fs pulse

Time-Domain THz: Core Components

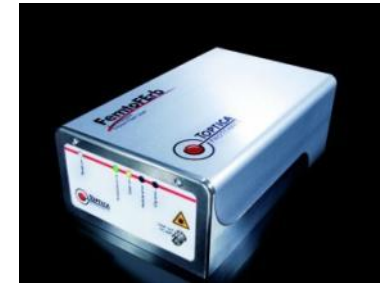


- 1** fs laser
- 2** Terahertz emitter
- 3** Translation stage

Time-Domain THz: Core Components (1)



FemtoFiber pro



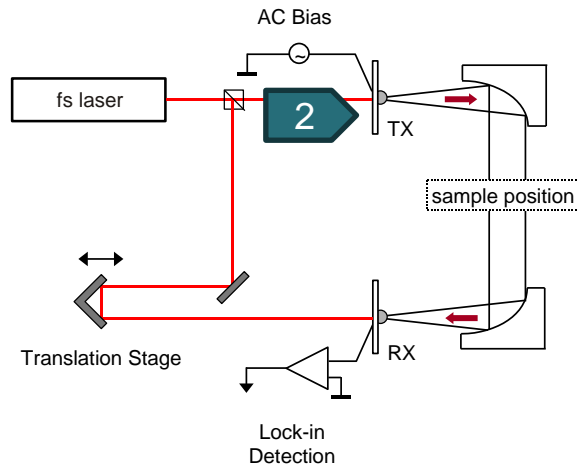
FemtoFiber smart

- 1** fs laser
- 2** Terahertz emitter
- 3** Translation stage

► Femtosecond fiber lasers

- ▷ 1560 nm or 780 nm
- ▷ Pulse width < 100 fs
- ▷ Average power 50 .. 350 mW
- ▷ Hands-off, push-button operation

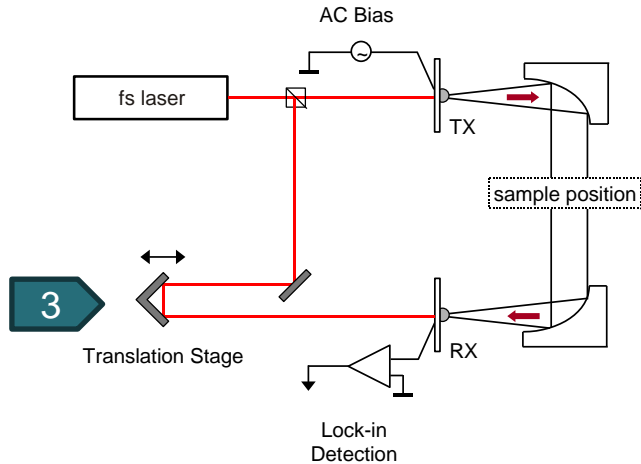
Time-Domain THz: Core Components (2)



- 1** fs laser
- 2** Terahertz emitter
- 3** Translation stage

- ▶ **Photoconductive switches**
 - ▷ GaAs (780 nm → 4 THz)
 - ▷ InGaAs (1560 nm → 4 THz)
- ▶ **Organic crystals**
 - ▷ DAST, OH1 (1560 nm → 10 THz)
- ▶ **Average power approx. 1 μW**

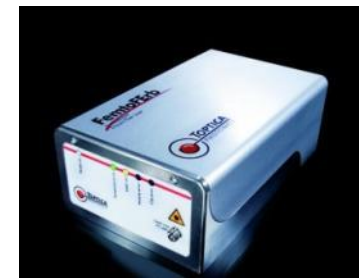
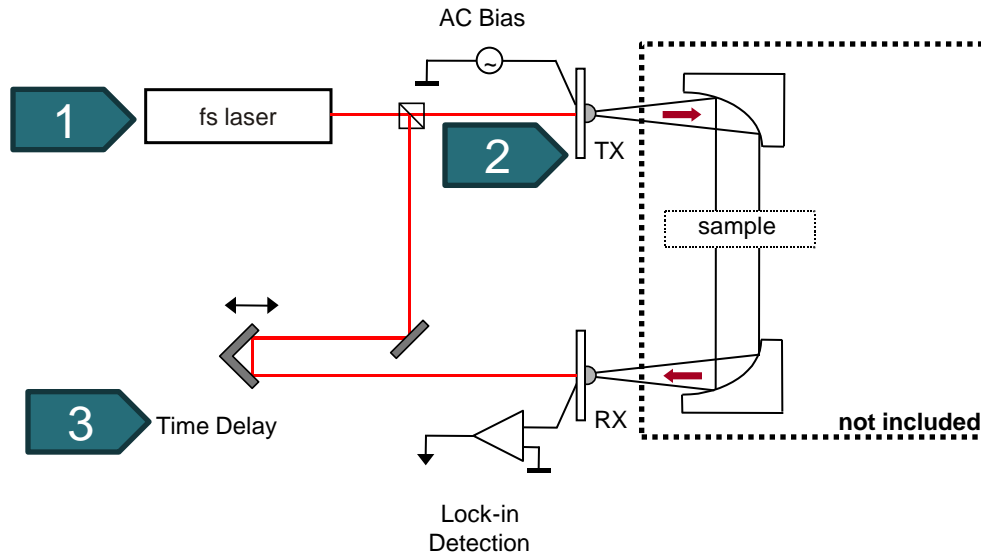
Time-Domain THz: Core Components (3)



- 1 fs laser
- 2 Terahertz emitter
- 3 Translation stage

- ▶ **3 types: translation, rotation, electronic**
 - ▷ Range > 100 ps, determines resolution
 - ▷ Scan accuracy determines SNR
 - ▷ Scan frequency determines measurement speed

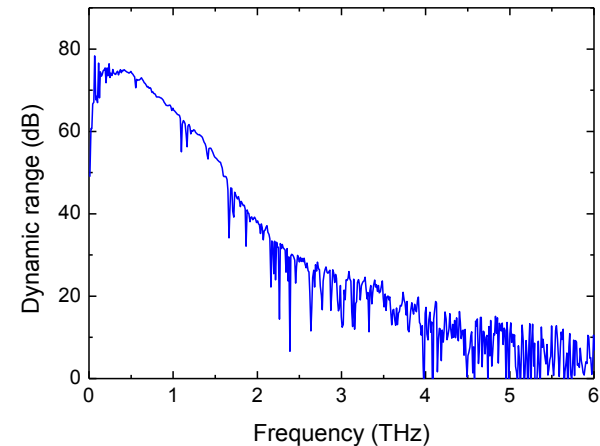
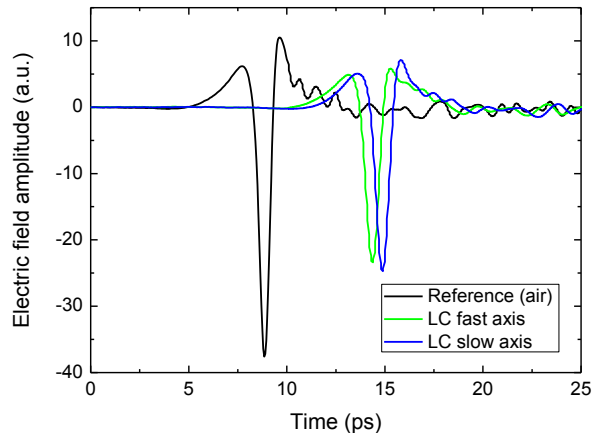
TeraFlash: Time-Domain THz Platform



- 1** Compact fs fiber laser (1560nm)
- 2** InGaAs/InP THz emitter and receiver
- 3** Fast mechanical delay (“Voice coil”)

TeraFlash – Time-Domain THz Platform

- ▶ Flexible usage due to fiber-coupled antennas
- ▶ Precise mechanical delay stage → high SNR
- ▶ “Fast Scan“ mode: 20 traces/sec, dynamic range > 55 dB, bandwidth 3 THz
- ▶ “Precise Scan“ mode: 20 sec/trace, dynamic range > 70 dB, bandwidth > 4 THz



- ▶ **Terahertz Bubbles**

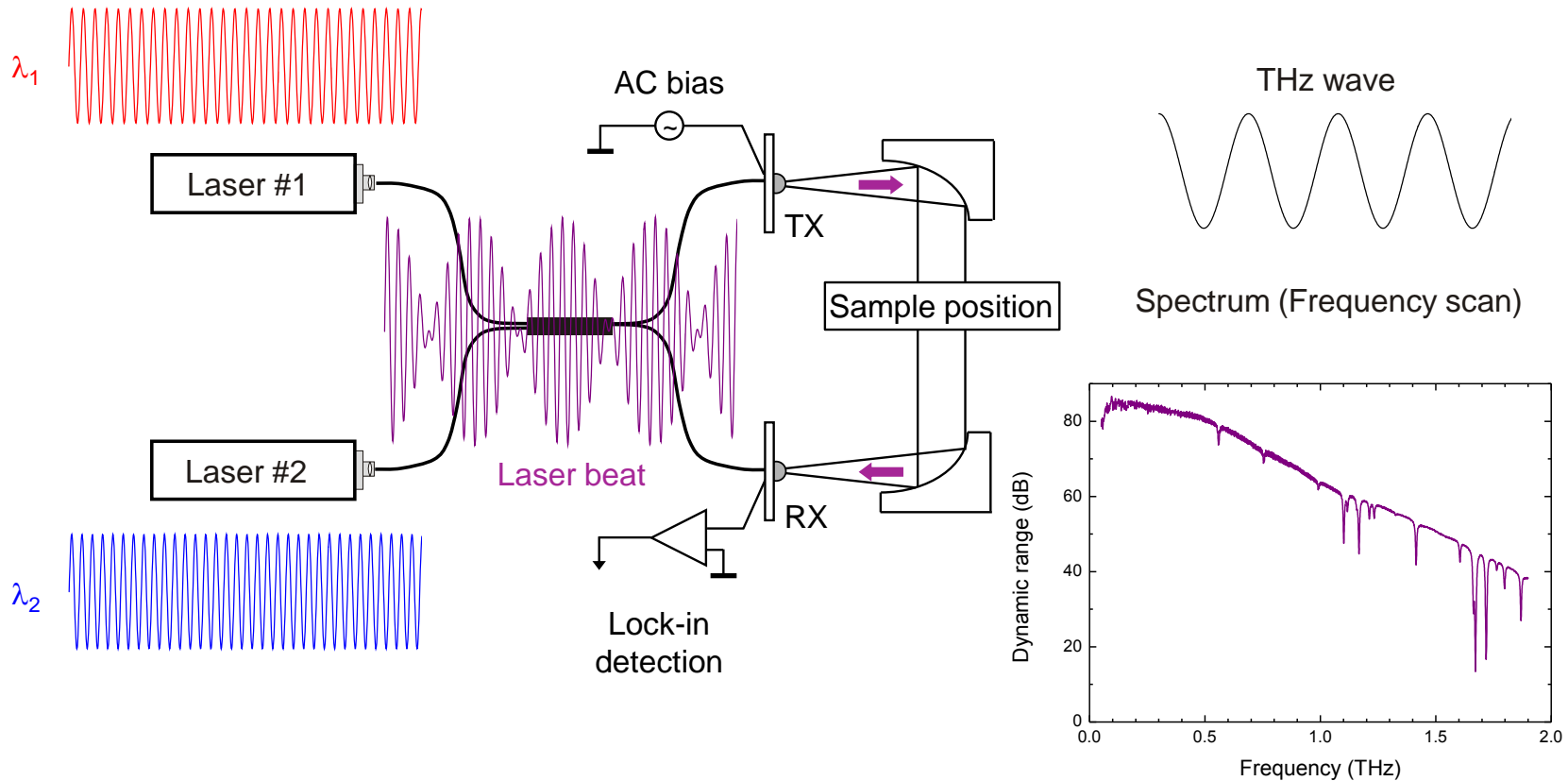
- ▶ **Time-Domain Terahertz**
 - ▷ Techniques and technology

- ▶ **Frequency-Domain Terahertz**
 - ▷ Techniques and technology

- ▶ **Application Examples**
 - ▷ Detection of toxic gases
 - ▷ Measurement of paint layers on automobiles
 - ▷ Paper humidity monitoring
 - ▷ Terahertz imaging

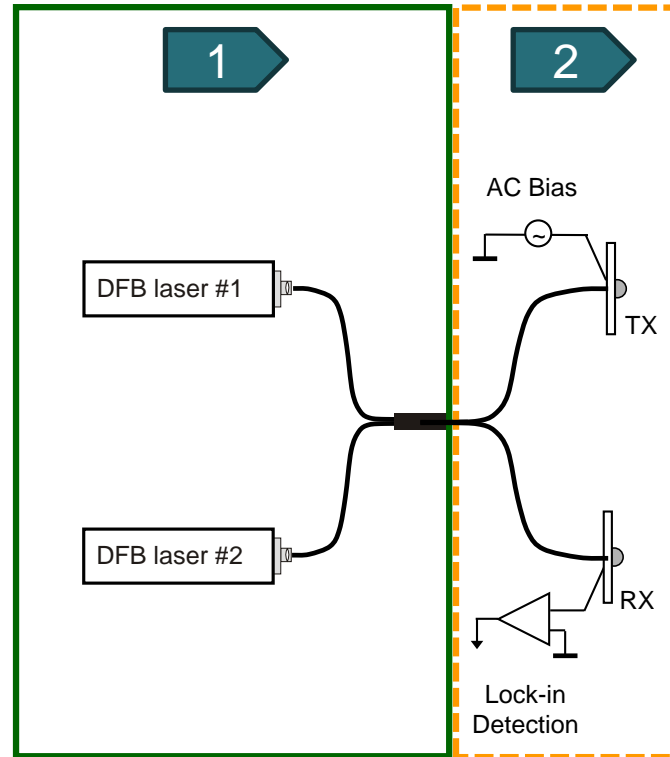
- ▶ **Summary**

Frequency-Domain Terahertz Generation



- ▶ Optical heterodyning of two DFB lasers on metal-semiconductor-metal antenna
- ▶ Two laser beams with adjacent wavelengths required

Frequency-Domain THz: Core Components



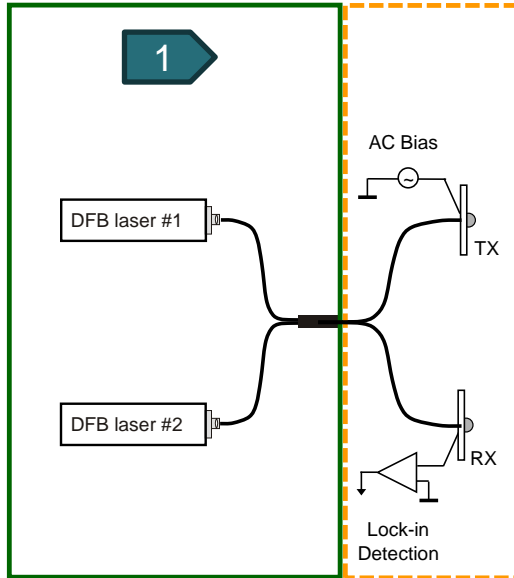
1

cw lasers

2

Photomixers

Frequency-Domain THz: Core Components



1

cw lasers

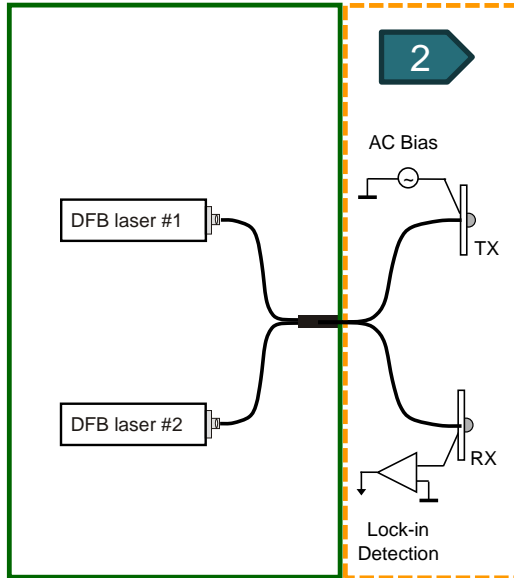
2

Photomixers

► Tunable DFB lasers

- ▶ 2 DFB diodes: 853 & 855 nm, or 1546 & 1550 nm
- ▶ Fiber-optic beam combination
- ▶ Highly-precise, computerized frequency control
- ▶ Difference frequency 0 – 2 THz

Frequency-Domain THz: Core Components

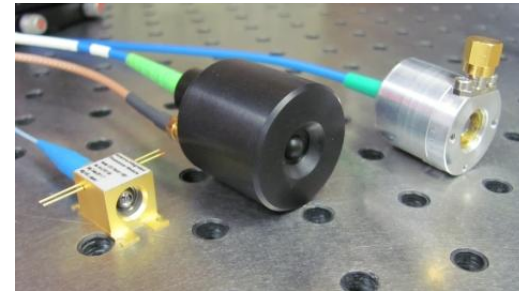
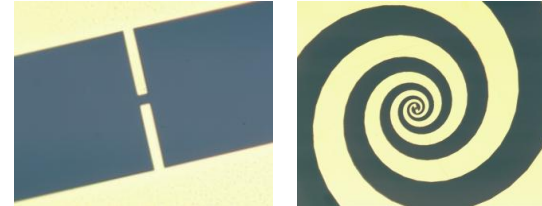


1

cw lasers

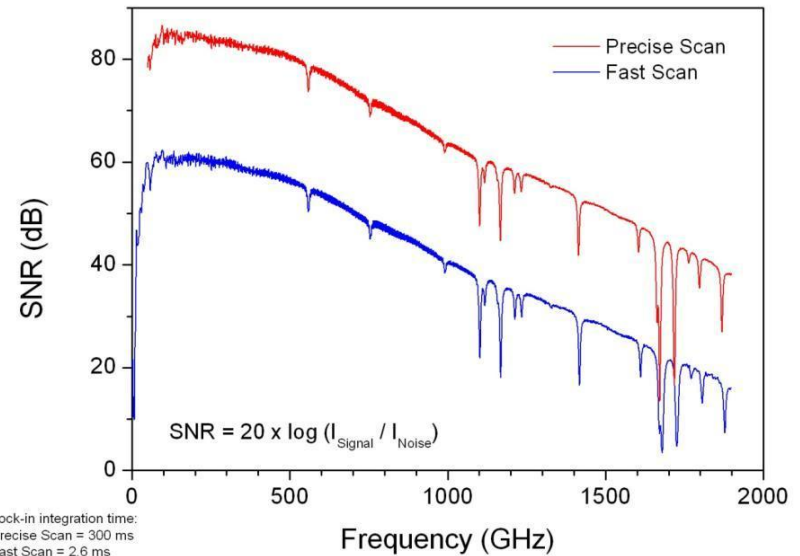
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Photomixers



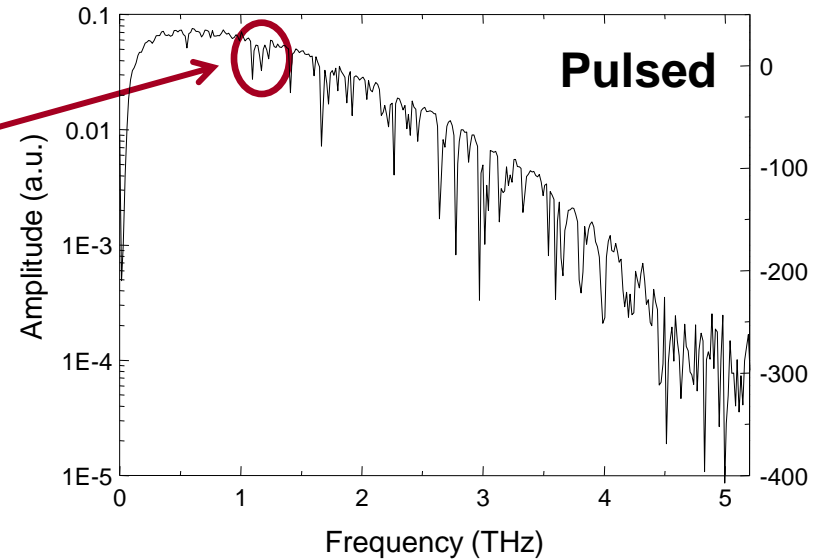
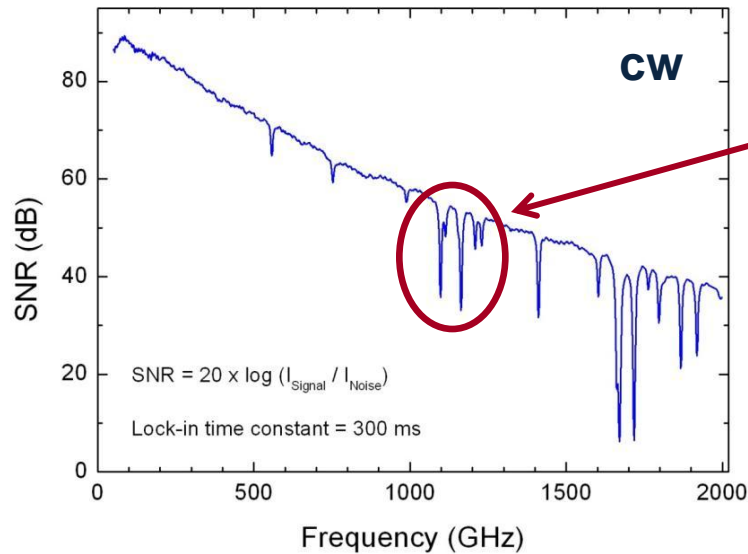
- ▶ **Photomixer = semiconductor with antenna structure**
 - ▷ GaAs (780 & 850 nm → maximum bandwidth and SNR)
 - ▷ InGaAs (1550 nm → telecom technology, potentially low-cost)
- ▶ **Max. power 2-4 μ W**

TeraScan – Frequency-Domain THz System



- ▶ **Twin-DFB laser with GaAs or InGaAs antennas**
- ▶ **System bandwidth up to 2 THz**
- ▶ **Peak dynamic range > 80 dB**
- ▶ **Frequency resolution 10 MHz**
- ▶ **Complete spectrum acquired in < 2 min. (with “fast scan“ option)**

Cw vs. Pulsed THz



	cw THz	Pulsed THz
Bandwidth	Max. ~ 2 THz, limited by laser	Max. 4 .. 10 THz, depending on emitter
SNR	Max. ~ 85 dB	Max. ~ 75 dB
Frequency resolution	10 MHz	10 GHz typ.
Acquisition time (complete spectrum)	Minutes to hours (resolution, lock-in time)	Seconds to minutes (delay line, resolution)

- ▶ **Terahertz Bubbles**

- ▶ **Time-Domain Terahertz**
 - ▷ Techniques and technology

- ▶ **Frequency-Domain Terahertz**
 - ▷ Techniques and technology

- ▶ **Application Examples**
 - ▷ Detection of toxic gases
 - ▷ Measurement of paint layers on automobiles
 - ▷ Paper humidity monitoring
 - ▷ Terahertz imaging

- ▶ **Summary**

Applications: Detection of toxic gases

▶ Task 1: Monitor air quality in public buildings

- ▷ Identify threatening chemicals in a “cluttered” background
- ▷ E.g. subway station: No false alarm from cleaning agents, perfumes, glue, paint, ...



▶ Task 2: Identify dangerous gases in smoke

- ▷ Optimize combustion processes
- ▷ Early warning in disaster sites



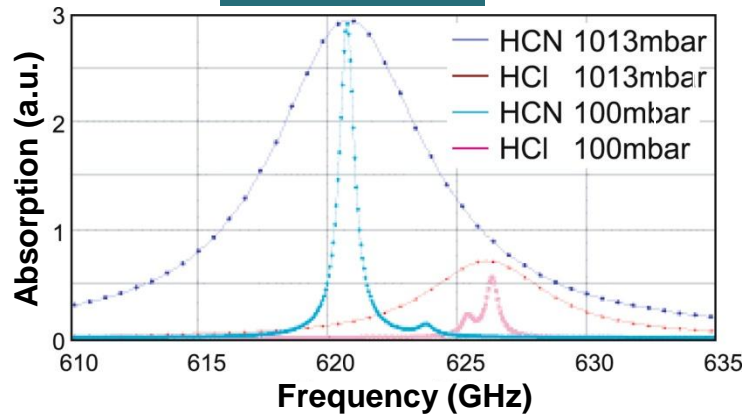
▶ Solution: Frequency-domain THz spectroscopy

- ▷ Increased sensitivity at low pressure (~ 100 mbar) \Leftrightarrow high-resolution spectroscopy

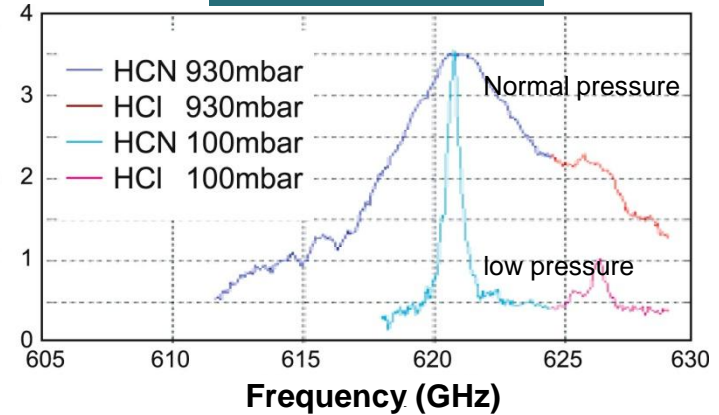


Applications: Detection of toxic gases

Simulation



Measurement



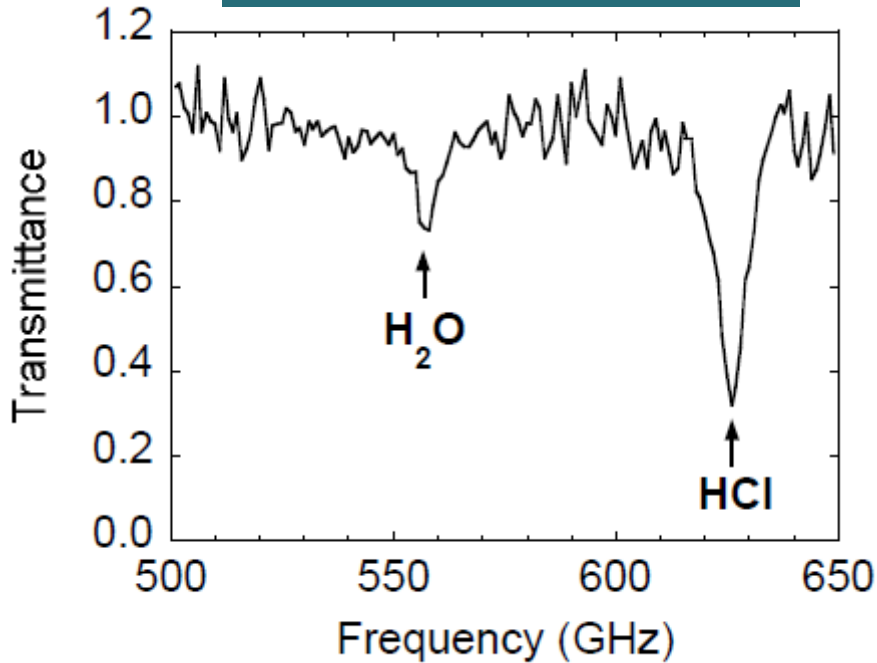
© A. Majewski, Goodrich Corp.

- ▶ **Compounds of gas mixture can be identified**
- ▶ **Benefits of THz vs. IR spectroscopy:**
 - ▷ All gases can be detected with one system
 - ▷ Strong absorption @ THz frequencies → detection even of trace amounts

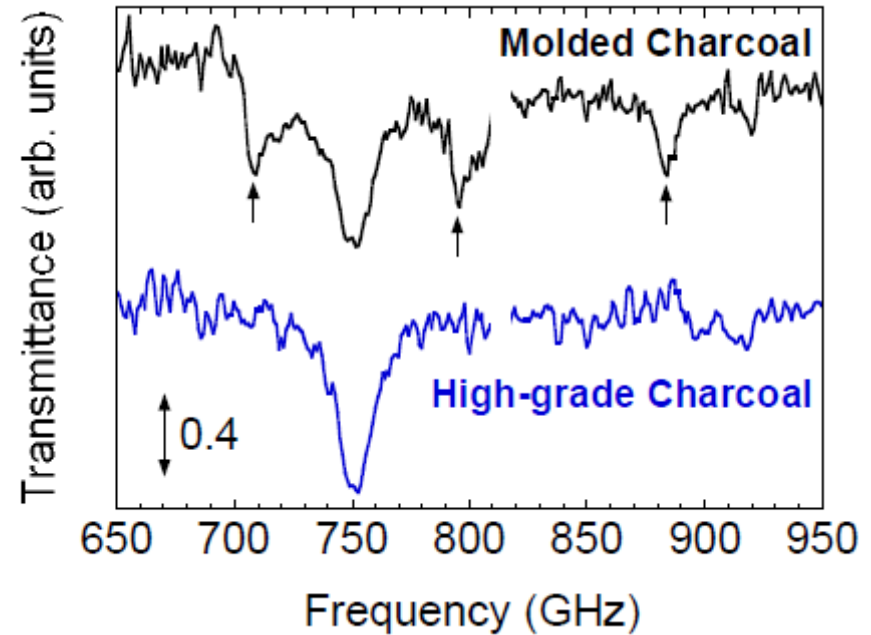


Applications: Detection of toxic gases

PVC smoke with HCl line



Charcoal smoke with HCN lines



- ▶ THz spectroscopy even works through black smoke
- ▶ Ongoing research @ Tokyo University + NTT, Japan



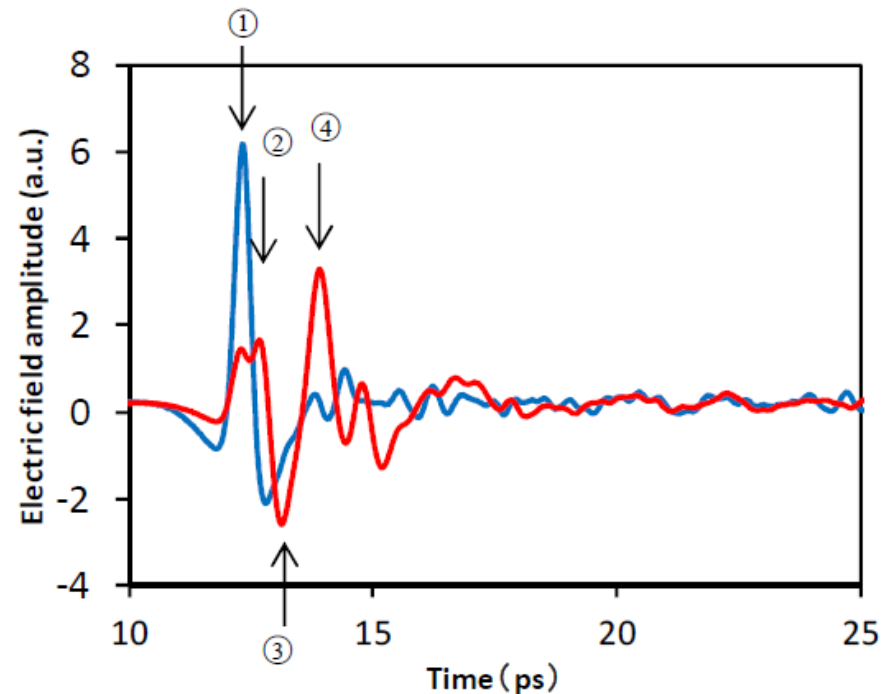
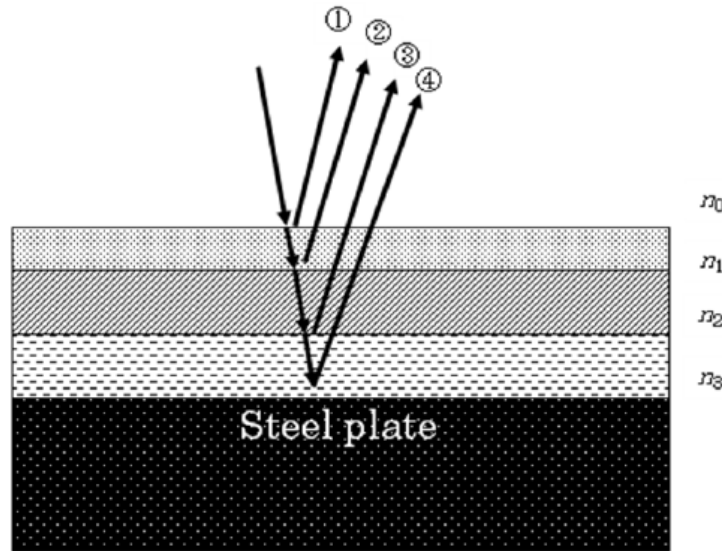
Applications: Measurements of Paint Layers

- ▶ **Task: Controlling the thickness of paint layers on automobiles**
 - ▷ Car paint consists of 3-4 layers (grounding, color, coat layer etc.)
 - ▷ Layer thickness typ. 15 .. 40 μm
 - ▷ Present measurement methods fail in the case of wet layers
 - ▷ UV and NIR don't work either – too much scattering

- ▶ **Solution: Time-domain THz spectroscopy**
 - ▷ Use time-of-flight techniques (= pulse “echoes”) to determine thickness of layers
 - ▷ Critical: layers with high metallic content



Applications: Measurements of Paint Layers



► Example: 3 layers on steel

- ▷ From top to bottom: (1) clear coating, (2) color layer, (3) middle coating, (4) steel plate
- ▷ Blue line: Mirror, red: automobile coating
- ▷ Individual layers can be resolved
- ▷ Accuracy: $\sim 2 \mu\text{m}$



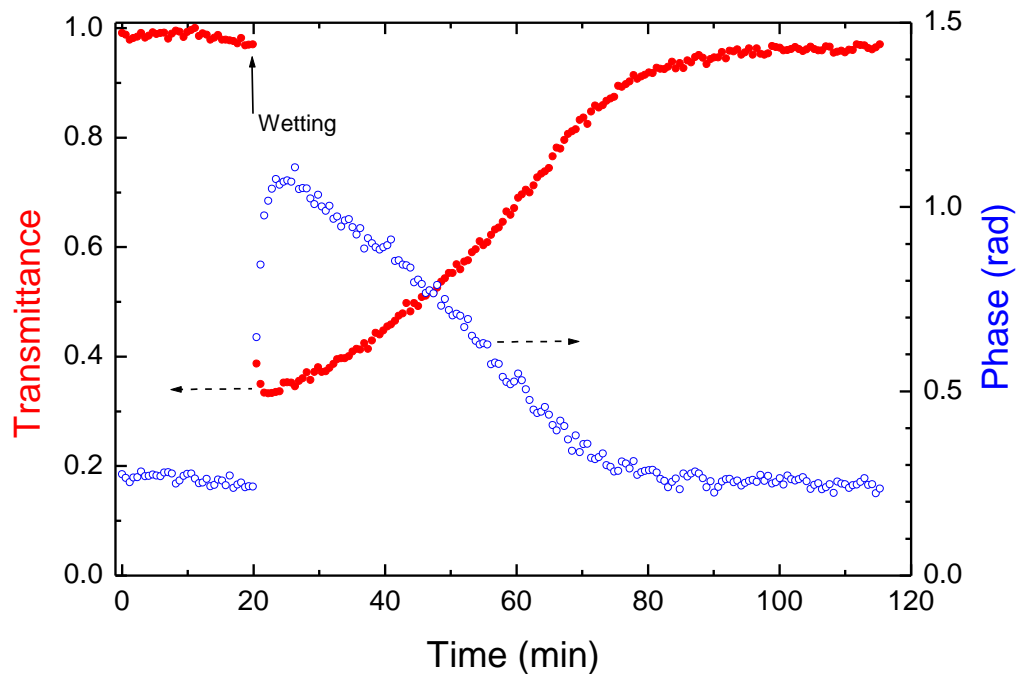
Applications: Paper Humidity Monitoring

- ▶ **Task: Measuring the water content in paper**
 - ▷ Essential parameter in paper production
 - ▷ Present techniques use radioactive (β) emitter – but: possible radiation exposure!
 - ▷ THz might provide safer alternative

- ▶ **Solution: Time-domain or Frequency-domain THz spectroscopy**
 - ▷ Water strongly absorbs THz waves
 - ▷ → Transmission or reflection measurements allow quantification of humidity level



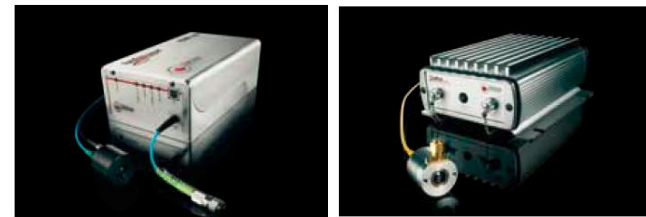
Applications: Paper Humidity Monitoring



Drying process of tissue, monitored @ 200 GHz

▶ **Example: Tissue sprayed with detergent**

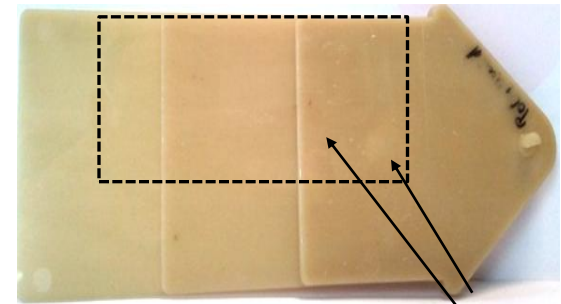
- ▷ Both terahertz amplitude and phase change with humidity level
- ▷ Amplitude and phase return to original values after ~ 1 hr



Applications: Terahertz Imaging

► Tasks: quite a few...

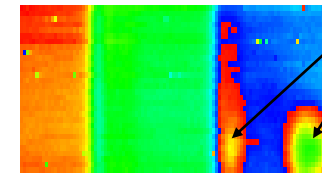
- ▷ Non-destructive testing
- ▷ Water-content imaging
- ▷ Security screening of parcels and envelopes
- ▷ ... possibly many more



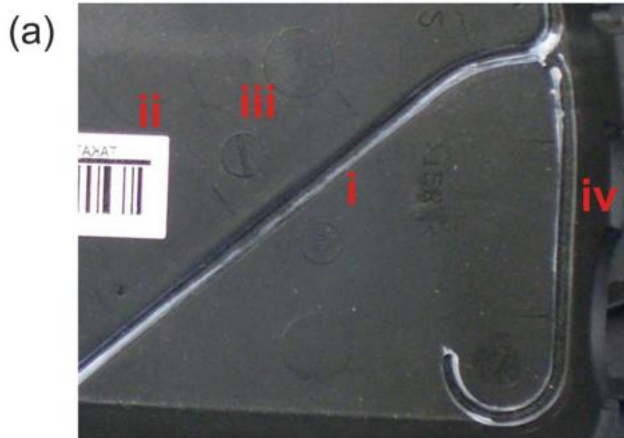
Air bubbles

► Solution: Laser-based and/or electronic sources

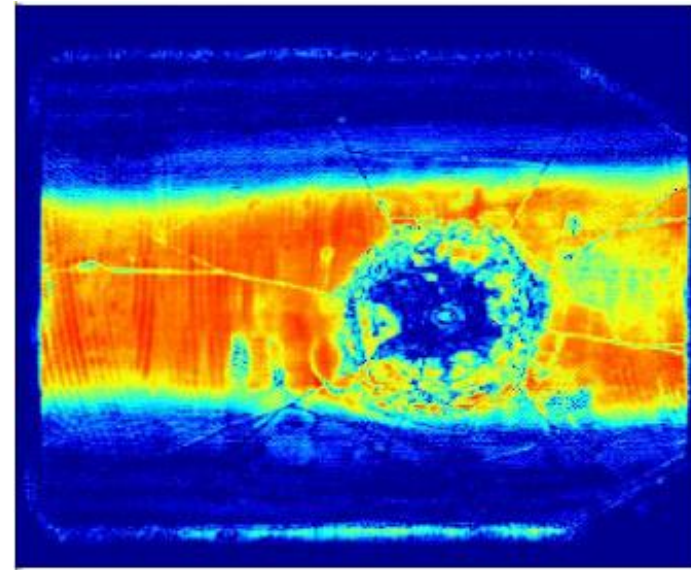
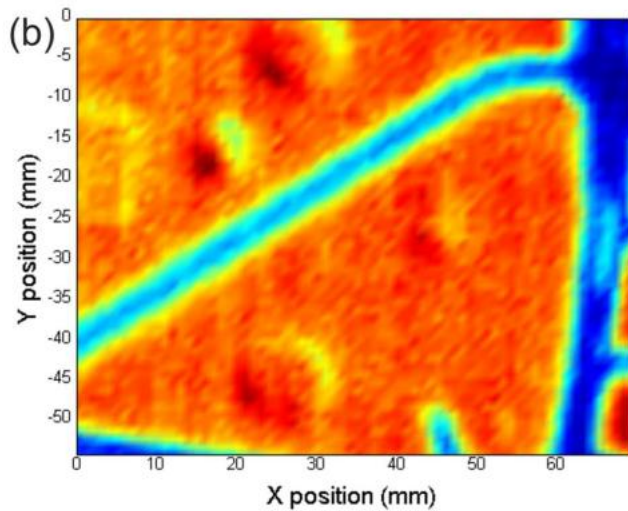
- ▷ Electronic: Image generated within minutes , no spectral information
- ▷ Laser-based: Image acquisition takes ~ 1 hr, but can be combined with spectral information
- ▷ 3D information possible



Terahertz Imaging: NDT



- (i) intended break line
- (ii) identification label
- (iii) stampings within the polymer
- (iv) retainer bars.



© SynView

Airbag cover with break line

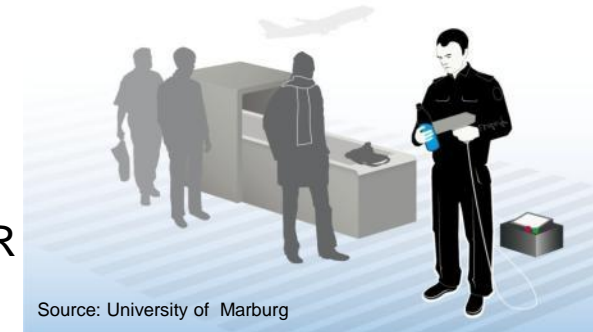
Bullet hole in Kevlar armor

Terahertz Perspectives: Spectroscopy

What Terahertz **can** do:

▶ Trace gas analysis

- ▷ Identification of toxic gases
- ▷ Detection of compounds in smoke (opaque for visible/IR light!)

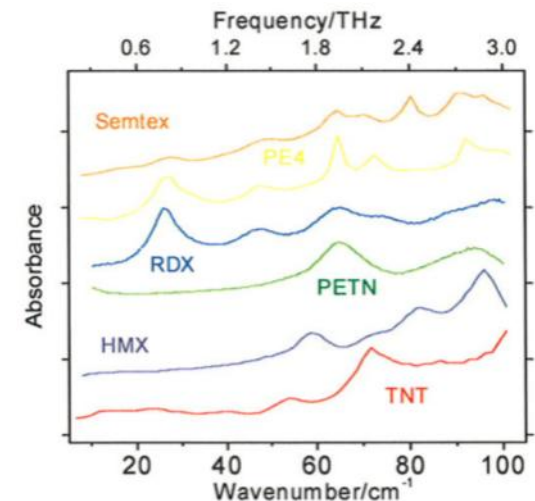


▶ Identification of hazardous materials

- ▷ Explosives in parcels / envelopes
- ▷ Bottled liquids can be identified via their refractive index

▶ Characterization of material properties

- ▷ Studies of semiconductors: carrier density, DC conductivity, ...

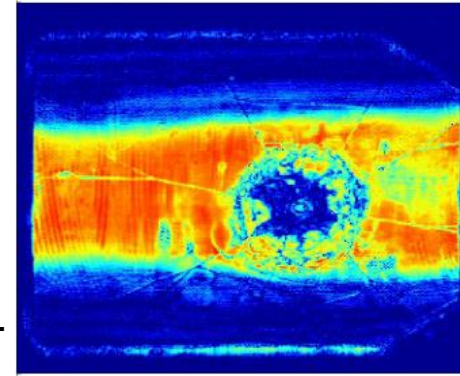


Terahertz Perspectives: Imaging

What Terahertz **can** do:

▶ Non-destructive testing

- ▷ Sub-surface cracks, voids, delaminations
- ▷ E.g. windmill blades, aircraft wings, bullet-proof body armor...



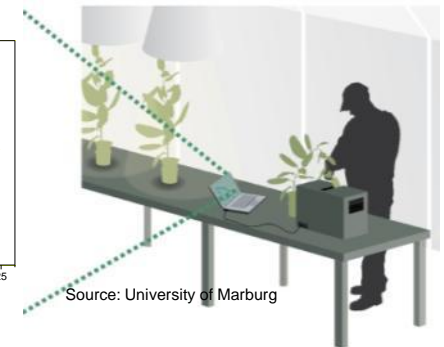
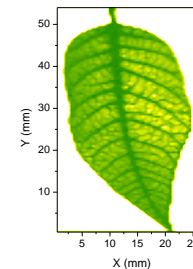
Source: SynView

▶ Detection and control of the water content

- ▷ Tool for selective cultivation of plants
- ▷ Inspection of the moisture in plastics and paper

▶ Homeland security: short-range imaging

- ▷ E.g. mail and parcel scanners
- ▷ Difficult to combine imaging speed and spectral investigations – usually only one is possible



Source: University of Marburg

Summary

- ▶ Terahertz systems have matured – first industrial implementations
 - ▷ Compact fs-fiber and diode lasers, fiber-pigtailed antennas

- ▶ Pulsed and cw techniques both have merits
 - ▷ Pulsed: highest bandwidth, shortest measurement time
 - ▷ cw: highest resolution, best dynamic range

- ▶ Electronic sources are suitable for THz imaging

Terahertz Sources from TOPTICA

▶ Time-domain THz platforms

- ▷ Ultrafast fiber lasers
- ▷ Fiber-coupled InGaAs antennas
- ▷ **New:** TeraFlash, spectroscopy platform



▶ Frequency-domain THz platforms

- ▷ Tunable cw diode lasers
- ▷ Fiber-coupled GaAs & InGaAs antennas
- ▷ **Top**Sellers: TeraScan 850 / 1550



Thank you for Your Attention!