State-of-the-Art Terahertz Systems and Their Applications

Presented by:

OSA Applied Spectroscopy Technical Group

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STATE-OF-THE-ART TERAHERTZ SYSTEMS AND THEIR APPLICATIONS

21 May 2019 • 10:00 EDT

OSA Applied Spectroscopy Technical Group

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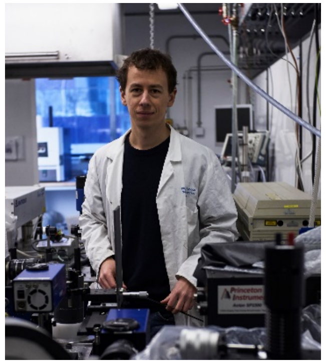
Technical Group Leadership Team(2018-2021)

Kaitlin Ann Lovering, Argonne National Laboratory, USA (Chemistry)

Sakshi Gupta, Laser Science & Technology Center, India (Optics & Lasers)



Benoit Fond, Otto-von-Guericke University of Magdeburg, Germany, (Thermodynamics & Fluid Mechanics)

Prasoon Diwakar, South Dakota School of Mines & Technology, USA (Mech Engineering)

Amartya Sengupta, Indian Institute of Technology Delhi, India (Physics)

Applied
Spectroscopy
Technical Group

Technical Group Website:
www.osa.org/AppliedSpectroscopyTG

Technical Group Social Media Sites:
LinkedIn
www.linkedin.com/groups/6992250

Applied Spectroscopy Technical Group Membership:
> 1500 Total Members
> 400 1st Priority Members

Scope of the Applied Spectroscopy Technical Group:
This group emphasizes the application of optical spectroscopy to detection and sensing problems in environmental, atmospheric, combustion, defense, and biomedical fields.

Examples of applied spectroscopy might include VNIR sensing and processing for food characterization and process control, optical techniques used in forensics, chem/bio detection and warning applications, and chemical analysis.

Mission

- **To benefit *YOU* and to strengthen *OUR* community**
- **Webinars, podcasts, publications, technical events, business events, outreach**
- **Interested in presenting your research? Have ideas for TG events? Contact us at amartya@physics.iitd.ac.in**

Contact your Technical Group and Get Involved!

TODAY'S WEBINAR:

Anselm Deninger, Toptica Photonics, Germany

Dr. Anselm Deninger studied physics at the University of Mainz (Germany). He obtained his PhD in 2000, having worked on the usage of laser-polarized helium-3 gas for magnetic-resonance imaging of lungs and airways. He subsequently joined TOPTICA as an R&D engineer in 2001 and helped develop TOPTICA's first commercial cw-terahertz system in 2007. As product manager, he is responsible for TOPTICA's terahertz product portfolio. Dr. Deninger has written or co-authored about 20 publications on THz technologies, including a book chapter on terahertz generation and detection with photomixers.

State-of-the-Art Terahertz Systems and Applications

Dr. Anselm Deninger, TOPTICA Photonics AG

OSA Technical Group Webinar

May 21, 2019

All Wavelengths.
190 nm - 0.1 THz

The Speaker

Dr. Anselm Deninger

- Studied physics at University of Mainz (Germany), PhD in 2000
- Joined TOPTICA in 2001, initially in R&D
- Worked on DFB lasers, frequency + coherence stabilization techniques
- Product manager since 2005
- Responsibilities include terahertz technologies – 12 years of terahertz experience

TOPTICA Group

Key Figures

Employees	300
Founded	1998
Locations	Munich + Berlin (Germany), USA, Japan, China

Technology

Diode Laser Systems	190 – 3500 nm
Ultrafast ps/fs Fiber Lasers	488 – 2200 nm, 5 – 15 µm
Terahertz Generation	0.1 – 6 THz

Terahertz @ TOPTICA

2019: Twelve years of terahertz activities

- Initial projects with Universities of Frankfurt + Darmstadt (Germany)
- First cw-THz system presented at LASER Munich 2007
- 12 years later: ~ 150 complete systems and > 500 lasers for THz generation in the field
- > 20 publications including a book chapter on THz written or co-authored by TOPTICA researchers
- Close collaborations with national and international research groups

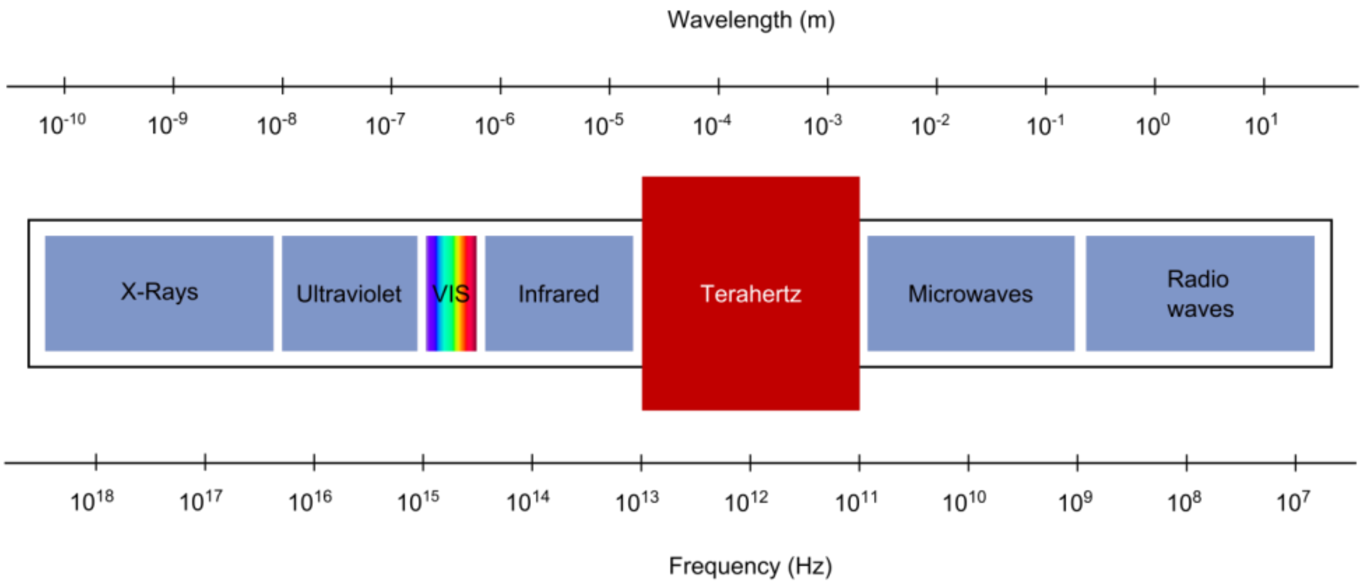
TeraFlash pro

TeraFlash smart

TeraScan

TeraSpeed

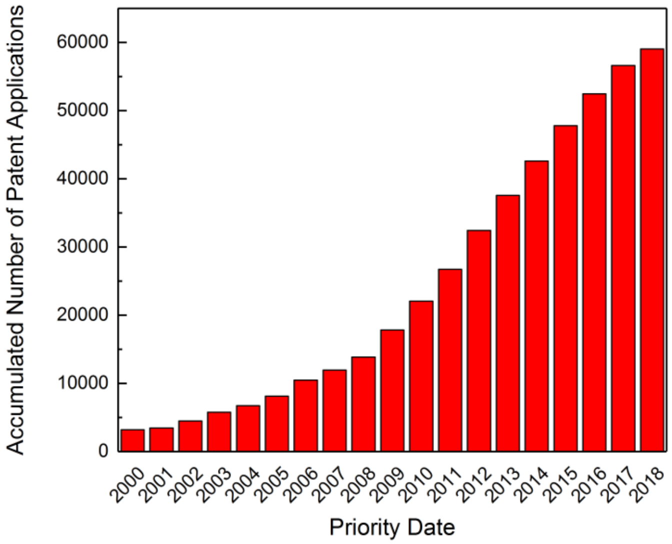
What is Terahertz Radiation?



- 1 THz ↔ 33 cm^{-1} ↔ 300 µm ↔ 4.1 meV
- Plastic, paper, cardboard, … transparent to THz waves → **Imaging**
- Many gases and organic solids show THz “fingerprints“ → **Spectroscopy**
- Non-ionizing – no health hazards

Moving out of the Lab…

- Google patents analysis, Jan. 2019: Accumulated number of terahertz-related applications grew by a factor of 18 between 2000 and 2018
- …with a factor of 3 between 2010 and 2018
- Various market reports forecast annual growth rates of ~ 20%
- Frost & Sullivan recently included THz sensors as one of top 50 emerging technologies
- **Terahertz technologies have matured are approaching productivity**



Integrated number of patent applications that include the term “terahertz“, 2000 – 2018

N. Vieweg et al., *SPIE Proc. 10925, Photonic Instrumentation Engineering VI; 109250U* (2019)

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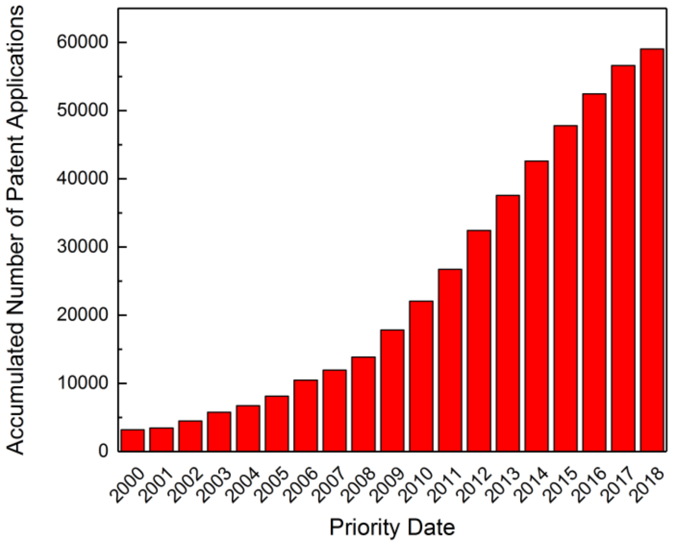
- **Terahertz technologies have matured are approaching productivity**

- This talk: **Optoelectronic THz generation + detection**
- Near-infrared laser light converts into THz
- Advantages: Broad bandwidth, high spectral resolution



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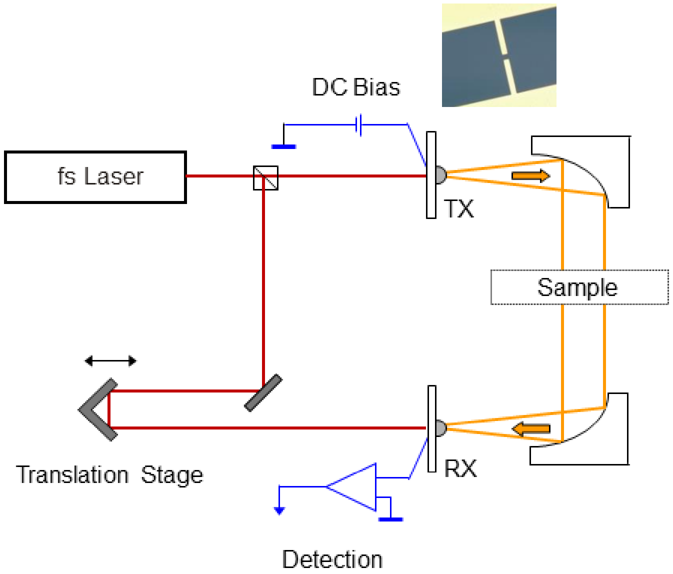
Outline

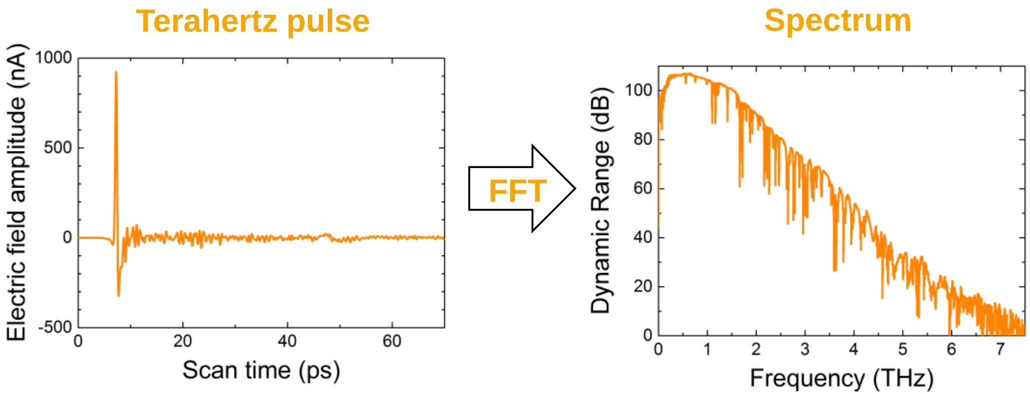
- Introduction
- Time-Domain Terahertz
    - Principles
    - Applications: Plastic Inspection, Paint Layers, Imaging, Hydration Monitoring
- Frequency-Domain Terahertz
    - Principles
    - Applications: Gas Sensing, Security
- Terahertz Screening
    - Principles
    - Application: Industrial Quality Control
- Summary

Time-Domain Terahertz

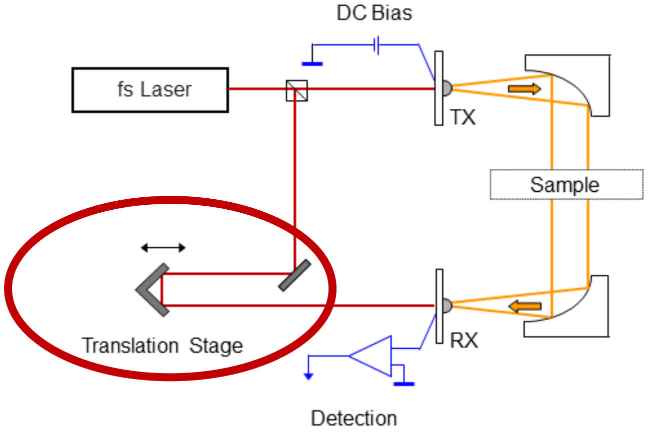
Time-Domain Terahertz Generation & Detection

- Output of femtosecond laser is split in two parts
- 1st pulse travels to transmitter → generates THz pulse
- …which interacts with sample (transmission, reflection)
- At receiver, THz pulse is sampled with time-shifted copy of laser pulse
- FFT of pulse trace produces THz spectrum





Why Delay Stages Matter…



Design of delay stage determines measurement speed

- Linear mechanical delays: several 10 traces/s
- Rotating delays: several 100 traces/s
- Electronic delays: several 1000 traces/s

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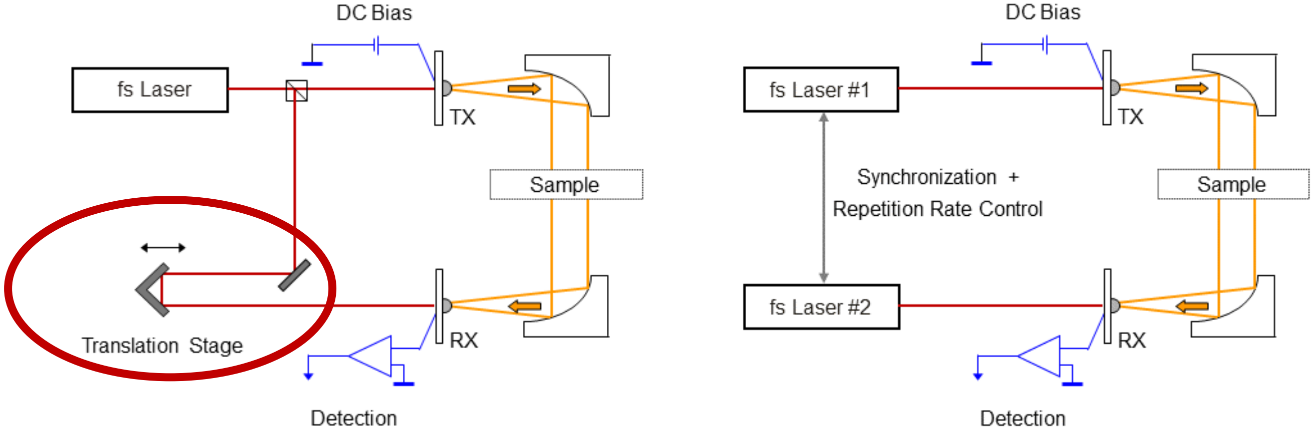

Mechanical delay

Electronic delay

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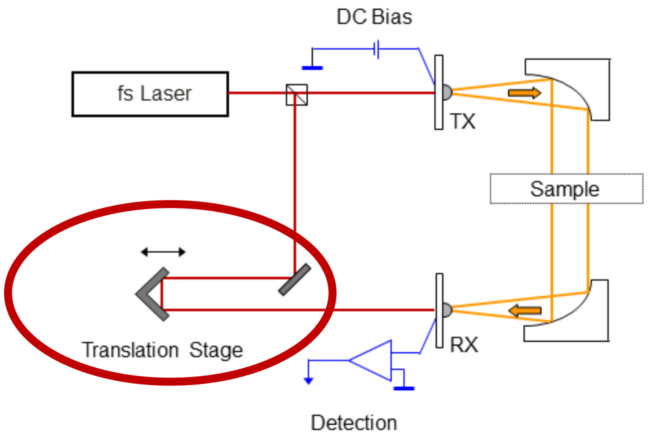
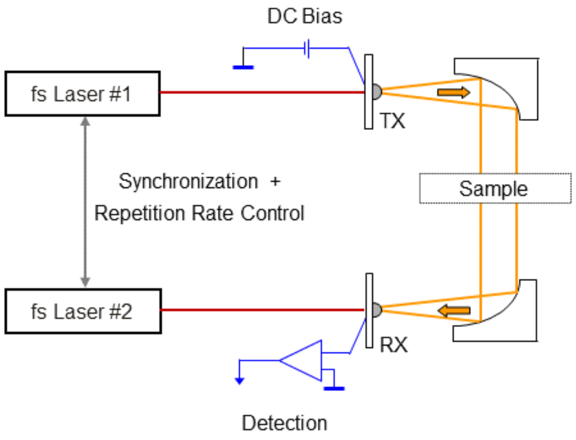
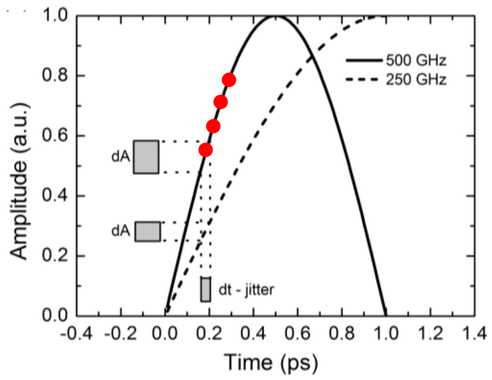






Mechanical delay

Electronic delay

Effect of jitter

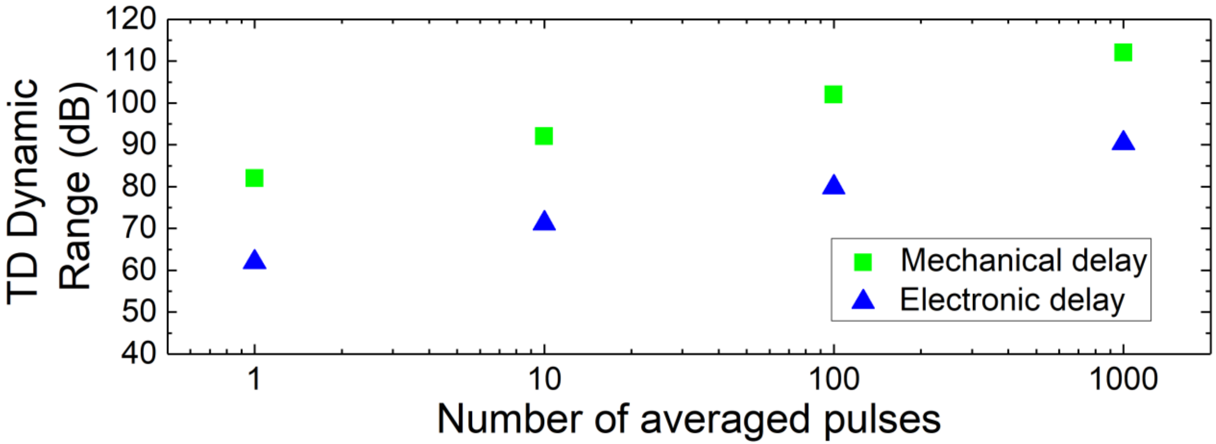
Design of delay stage determines measurement speed

- Linear mechanical delays: several 10 traces/s
- Rotating delays: several 100 traces/s
- Electronic delays: several 1000 traces/s

Timing jitter determines signal quality

- Short laser pulse “scans“ longer THz pulses
- Any uncertainty *dt* causes amplitude error *dA*
- Trace averaging without jitter reduces noise
- Trace averaging with jitter reduces THz signal

Mechanical vs. Electronic Delays (I)

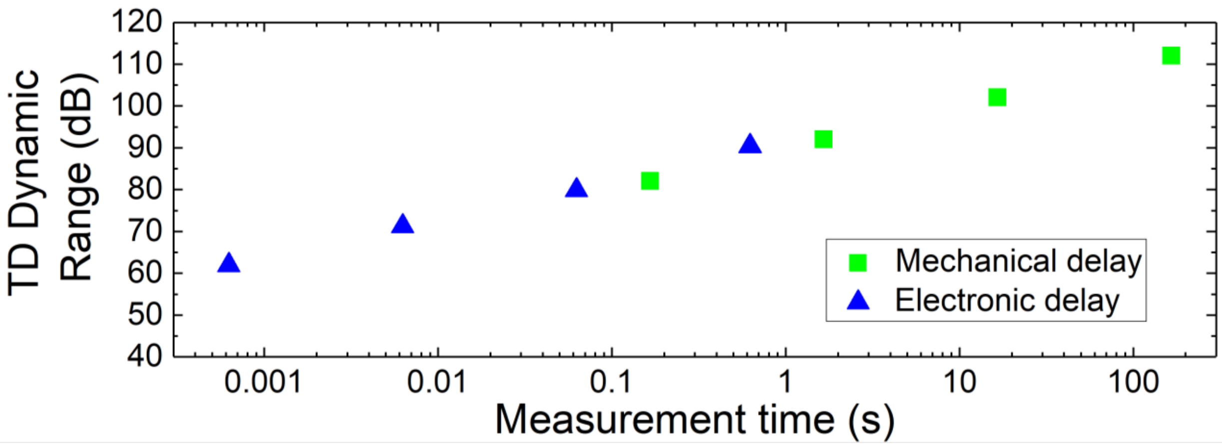


Factor of 10 in jitter ⬄ 20 dB difference in dynamic range

- Precise mechanical delay stages achieve lowest jitter
- → Higher dynamic range for the same number of averages
- Electronic delays have an advantage in terms of measurement speed

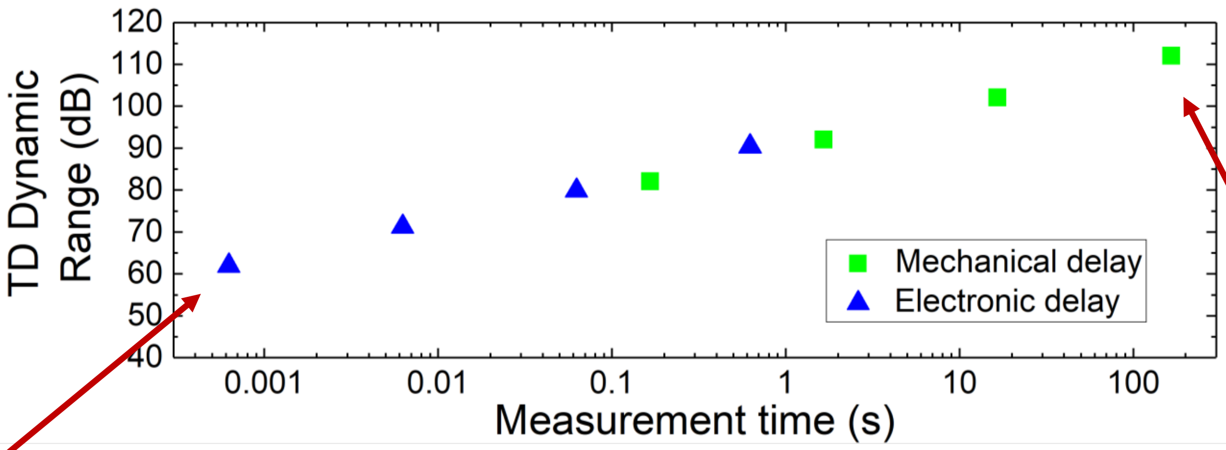
M. Yahyapour et al., *Appl. Sci.* **9** (2019) 1283

Mechanical vs. Electronic Delays (II)



Comparable performance in the same measurement time

Mechanical vs. Electronic Delays (II)



Comparable performance in the same measurement time

"Top speed":

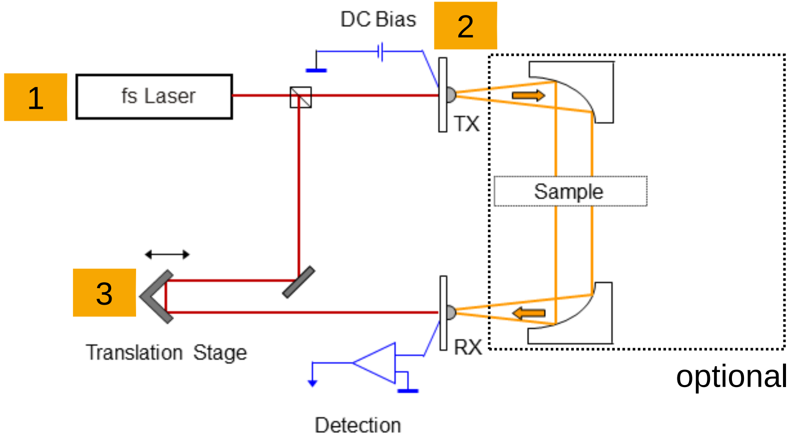
TeraFlash smart

"Top performance":

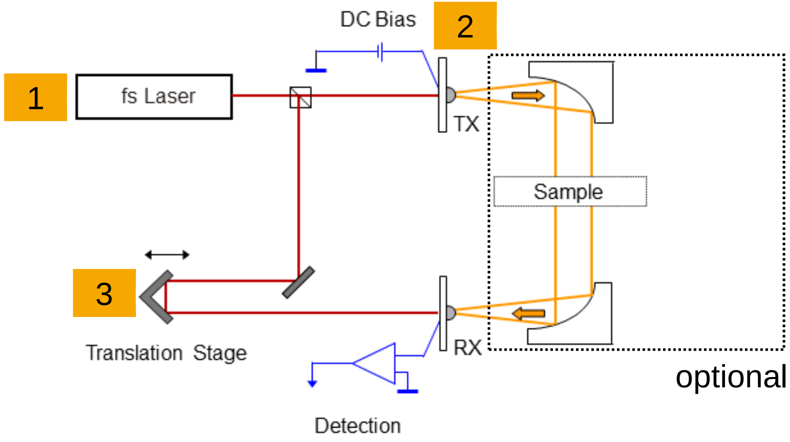
TeraFlash pro

TOPTICA PHOTONICS

TeraFlash pro: Components

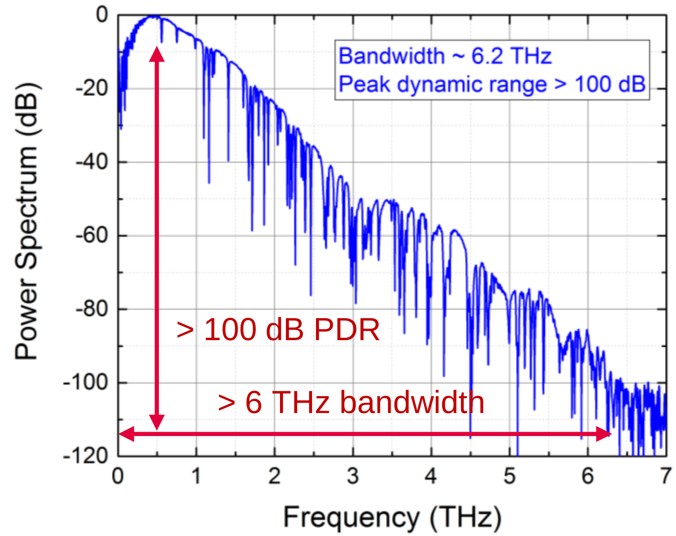


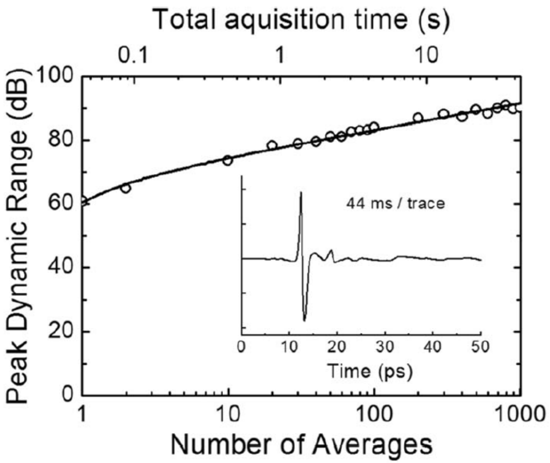
TeraFlash pro: Components



1	Femtosecond fiber laser: 1.5 µm, 100 MHz, < 60 fs, carefully designed fiber delivery
2	InGaAs antennas: Fiber-pigtailed package, ~ 30 µW average power
3	Mechanical delay stage: Highly precise voice coil

TeraFlash pro: System Performance



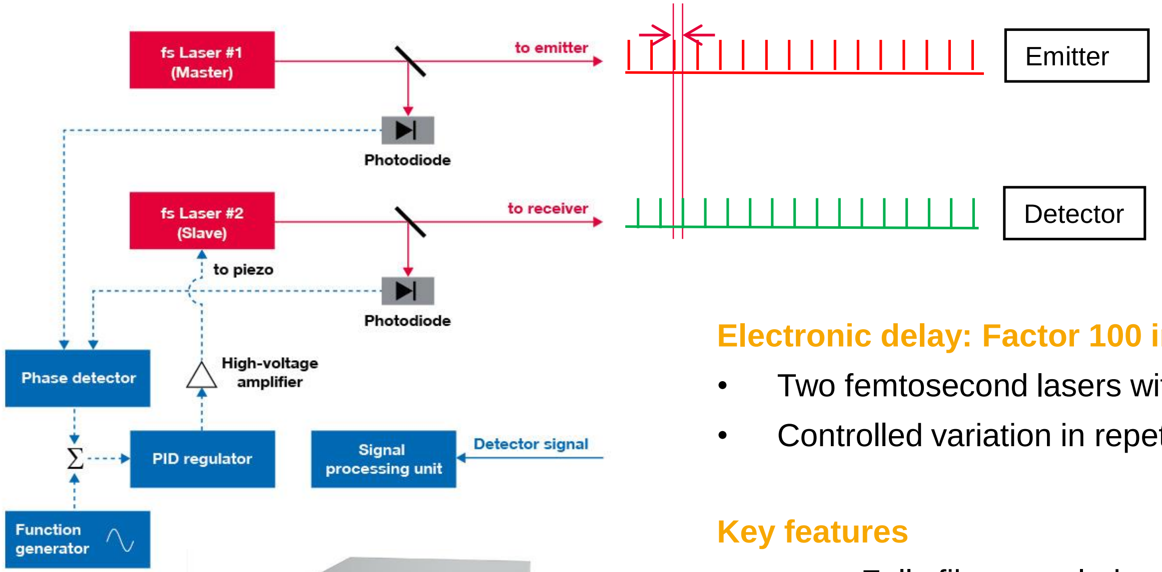


N. Vieweg et al., *J. Infrared Milli THz Waves* **35** (2014) 823

Measurement speed up to 40 traces/s

- Dynamic range reaches > 90 dB within less than 1 minute
- **Bandwidth > 5 THz (7 THz demonstrated)**
- Layer thickness measurements down to ~ 10 µm

Electronically Controlled Optical Sampling (ECOPS)



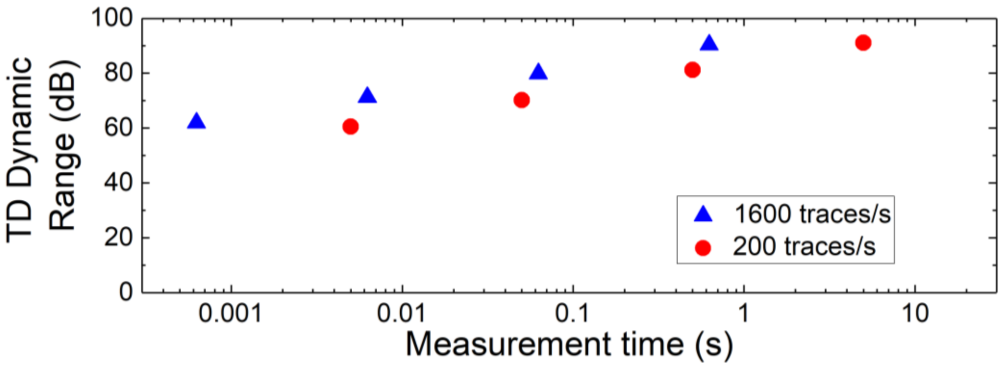
Electronic delay: Factor 100 in speed

- Two femtosecond lasers with synchronized repetition rates
- Controlled variation in repetition rate of “slave“

Key features

- Fully fiber coupled, external fiber length 10.5 m
- Flexible settings:
  - > 150 ps @ 1600 traces / sec
  - > 400 ps @ 800 traces / sec
  - > 700 ps @ 200 traces / sec
- Patented technology

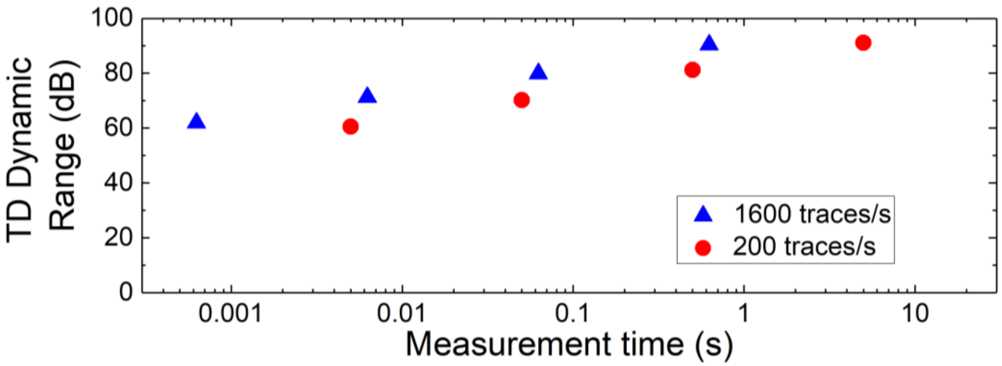
TeraFlash smart: System Performance

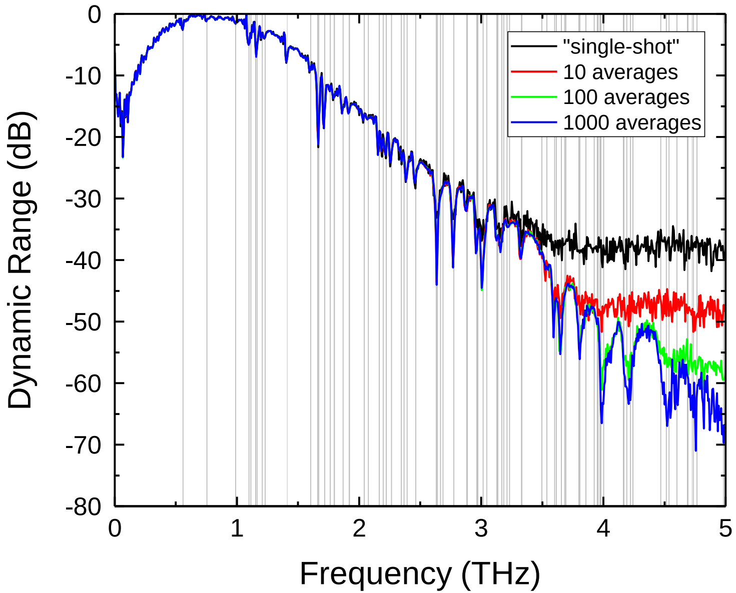


Time domain:

- Single-shot measurement completed in 0.6 ms (1600 pulse traces per second)
- Time-domain dynamic range: ~ 60 dB single-shot, ~ 90 dB within 1 s
- → Excellent instrument for layer thickness measurements

TeraFlash smart: System Performance





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Frequency-domain:

- Single-shot bandwidth ~ 3 THz @ 1600 traces/sec
- Averaging over 0.6 s: bandwidth ~ 4.7 THz

M. Yahyapour et al., *Appl. Sci.* **9** (2019) 1283

Application: Plastic Inspection

Goal: Assess the wall thickness of polymer pipes or bottles

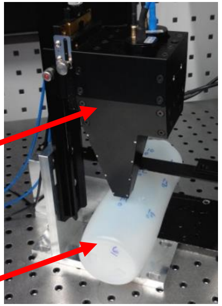
- Thinner walls help reduce material costs
- …but: Mechanical stability must be guaranteed!
- In-line monitoring during production desirable

Solution: TD-THz reflection measurements

- Each interface produces a pulse "echo"
- Time between two echoes is proportional to layer thickness (and refractive index)
- Method benefits from high dynamic range of state-of-the-art systems

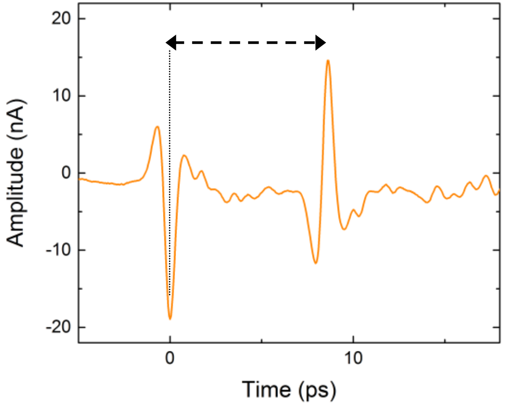
Reflection head

HDPE bottle



Δt = 8.60 ps

Layer thickness = 843 μm

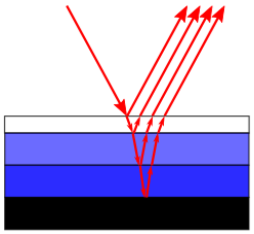


Wall thickness of PE bottle

Application: Paint and Coating Layers

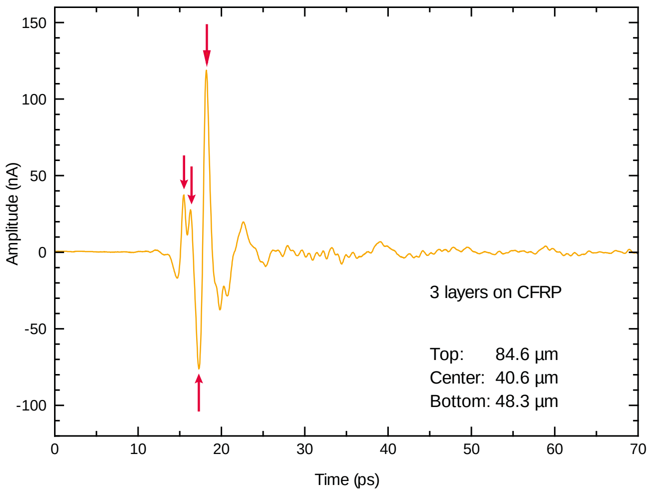
Goal: Control the thickness of paint and coating layers

- Car paint usually consists of 3-4 layers (primer, color, top coat), each of 10 .. 40 µm thickness
- Conventional methods fail if substrate is non-metallic



Solution: TD-THz reflection measurements

- Time-of-flight techniques resolve individual layers
- Thickness measurements down to 10-20 µm demonstrated (depending on material)
- Ternary and quaternary structures have been resolved



Pulse echoes of 3 coating layers on CFRP

Application: Terahertz imaging

Goal: Non-destructive testing

- Wealth of applications: Search for defects, voids, delaminations, quality control of sub-surface structures in polymer materials

Solution: TD-THz transmission / reflection imaging

- Complete pulse trace available for each image pixel
- → Spectroscopic information available
- → Data filtering both in the time-domain and frequency-domain possible

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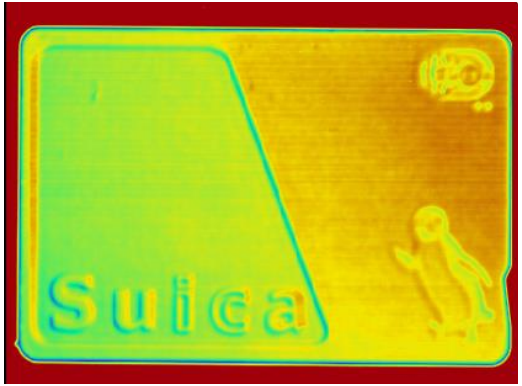

Reflectivity image

Japanese pre-paid public transport card

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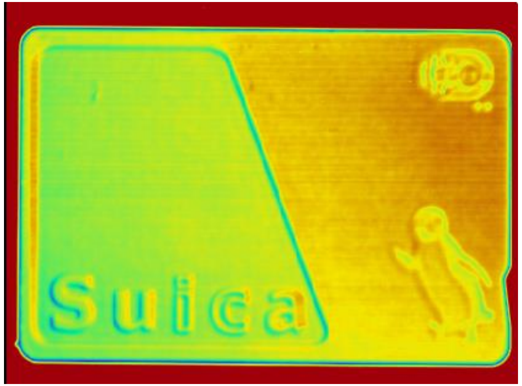

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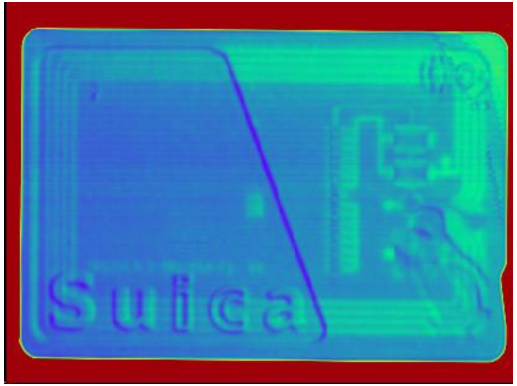


Front-side reflection removed

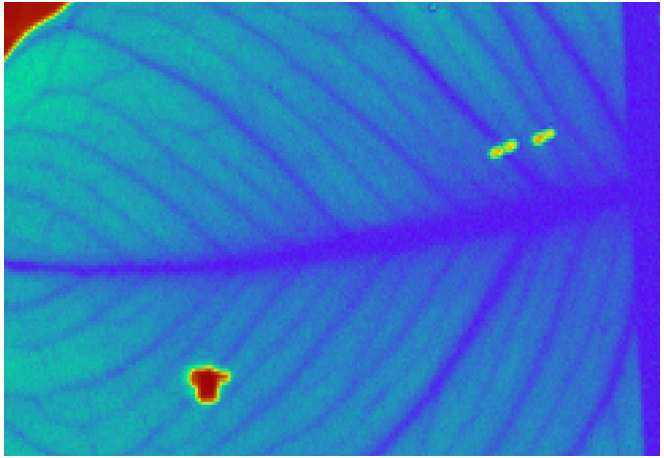
Application: Hydration monitoring

Goal: Survey the hydration status of plants

- Plant cultivation in arid areas requires careful management of water resources
- Terahertz measurements can help to optimize irrigation strategies

Solution: TD-THz reflection (transmission) imaging

- Water provides a strong contrast in terahertz imaging
- Method also suitable for humidity measurements in paper, polymers, ceramics, …

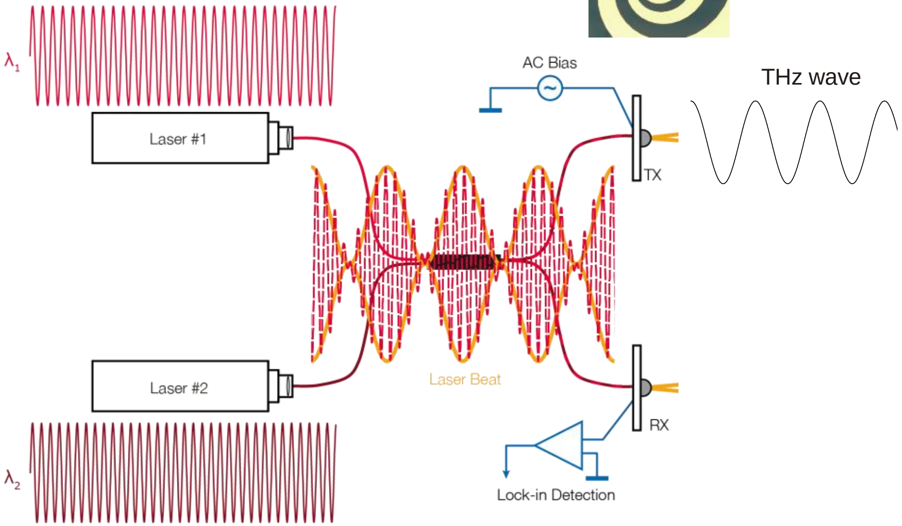


Water-contrast THz imaging:
Devil's ivy (Epipremnum aureum) plant leaf with holes

Frequency-Domain Terahertz

Frequency-Domain Terahertz Generation

- Two lasers @ adjacent frequencies illuminate photomixer
- Applied bias → Photocurrent, modulated at beat frequency
- Surrounding antenna emits THz wave
- Terahertz beam is monochromatic
- Tuning the lasers changes THz wavelength



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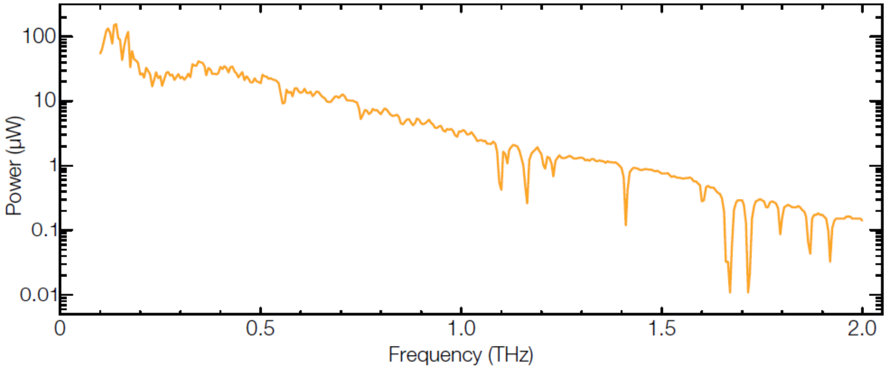
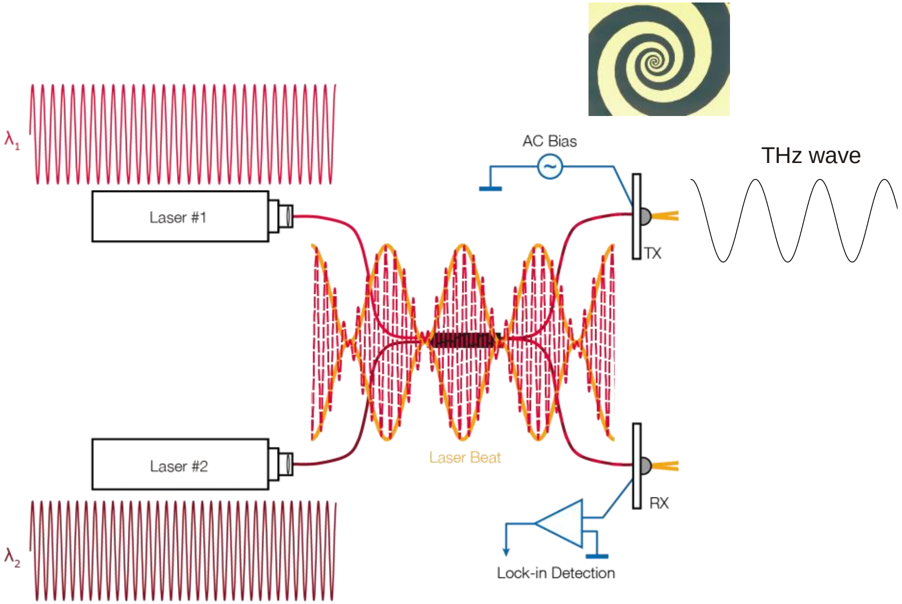




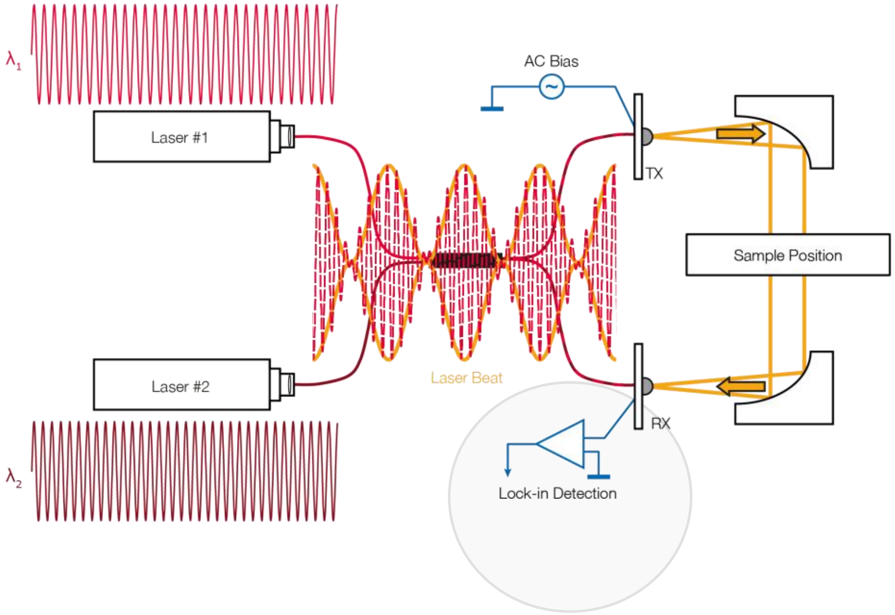
Frequency-Domain Terahertz: Signal Detection

Coherent signal detection

- Second – unbiased – photomixer serves as THz receiver
- THz wave generates time-varying voltage signal U(t)
- Laser beat modulates the photoconductance G(t)
- Photocurrent $\propto$ U(t) x G(t)

Proportional to THz electric field

And: depends on phase between U(t) and G(t)



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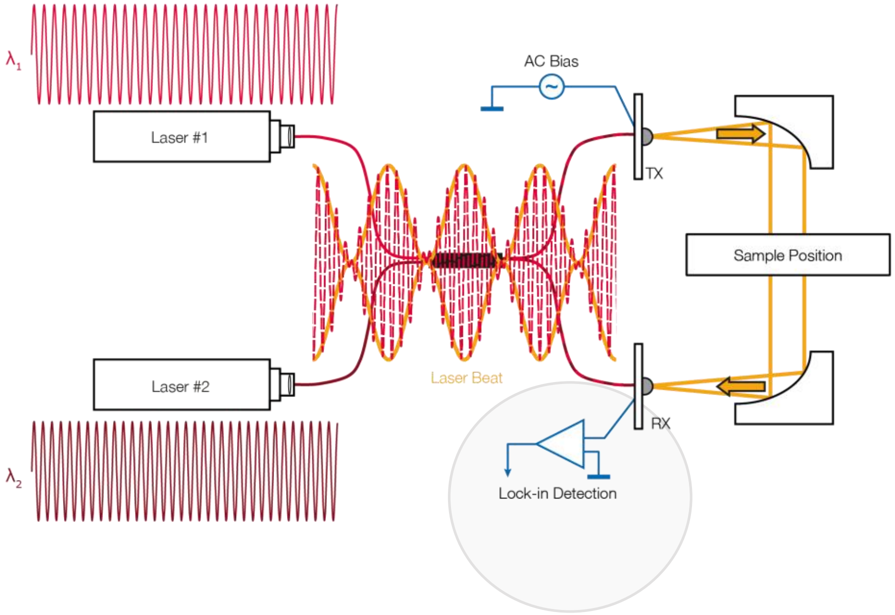
And: depends on phase between U(t) and G(t)

Lock-in detection:

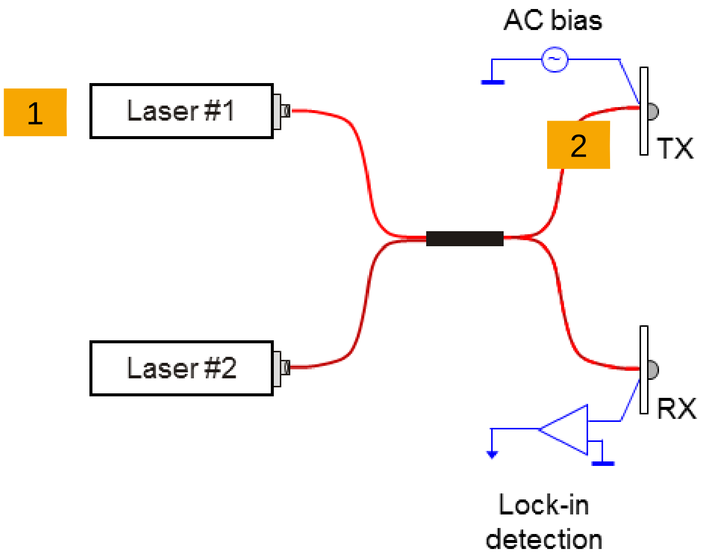
- Short integration time ⇔ high measurement speed

(~ 30 s / spectrum)

- Long integration time ⇔ lower noise floor



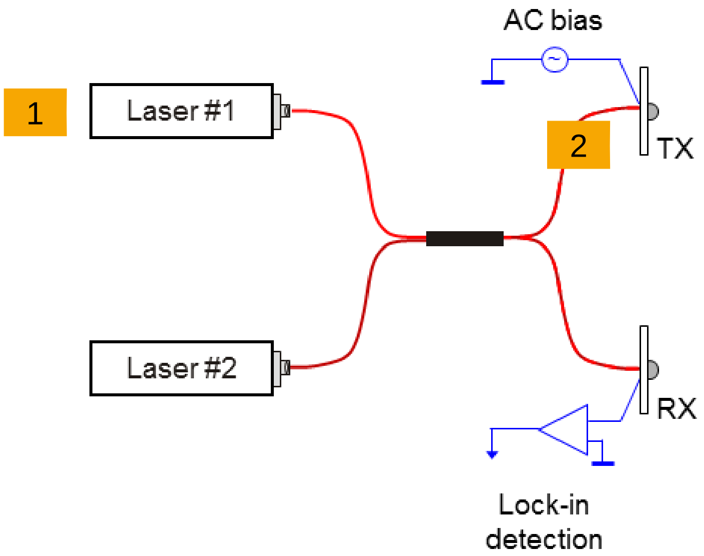
TeraScan Components



TeraScan 1550

A. Roggenbuck et al., *New J. Phys.* **12** (2010) 43017
D. Stanze et al., *J. Infrared Milli Terahz Waves* **32** (2011) 225
A. Deninger et al., *J. Infrared Milli Terahz Waves* **36** (2015) 269

TeraScan components



TeraScan 1550

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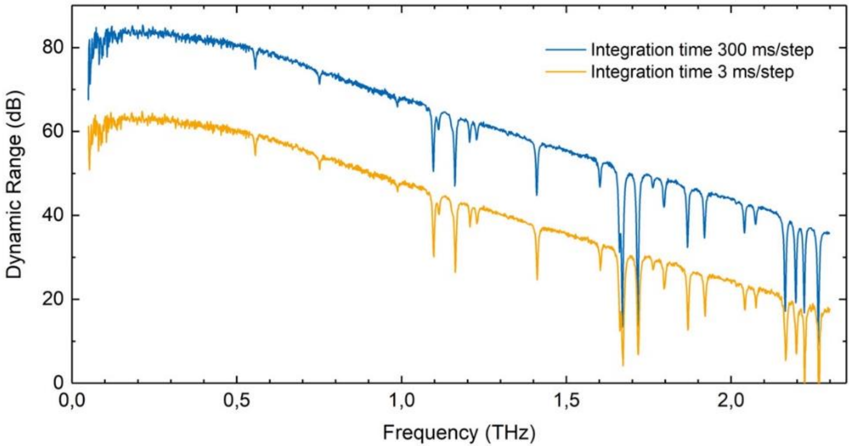
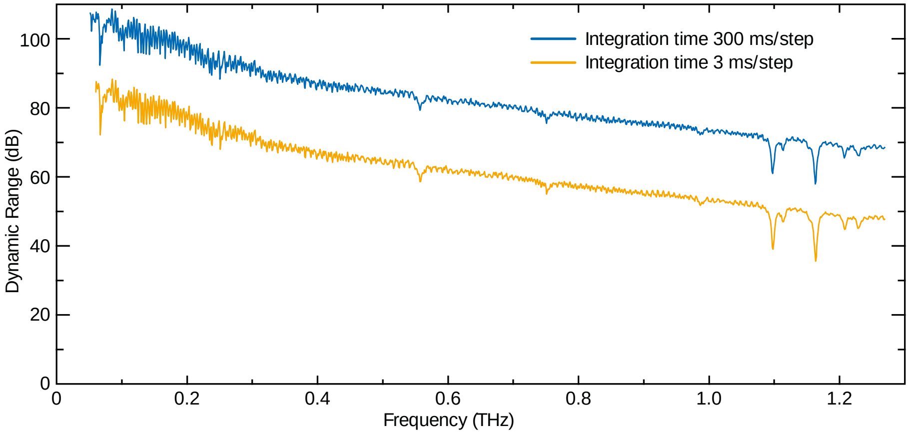
1 DFB diode lasers: λ ~ 0.8 µm or λ ~ 1.5 µm

2 GaAs or InGaAs photomixers: up to 100 µW output power, peak dynamic range ~ 100 dB

3 High-precision electronics: computerized frequency control, single-MHz frequency steps possible

TeraScan 780 and TeraScan 1550





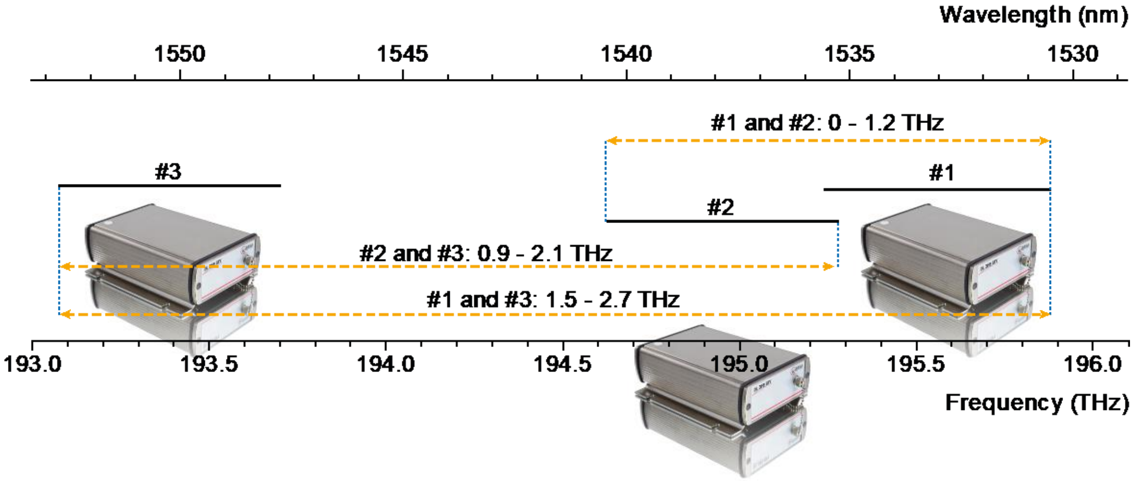
TeraScan 780

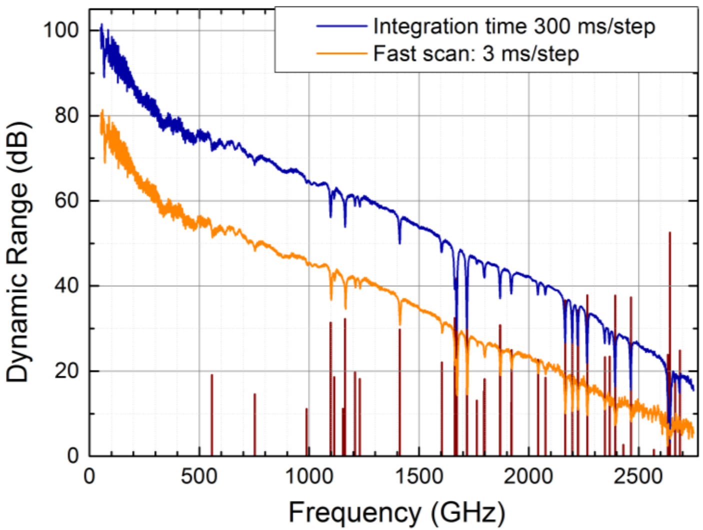
TeraScan 1550

Pre-configured systems

- State-of-the-art GaAs or InGaAs photomixers
- Highest bandwidth: **TeraScan 780**
- Highest dynamic range: **TeraScan 1550**

Tuning Range Extension



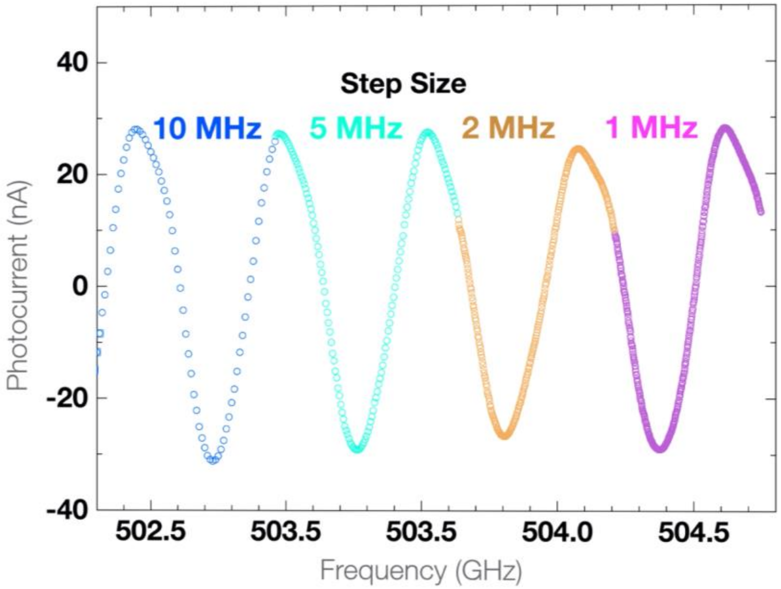


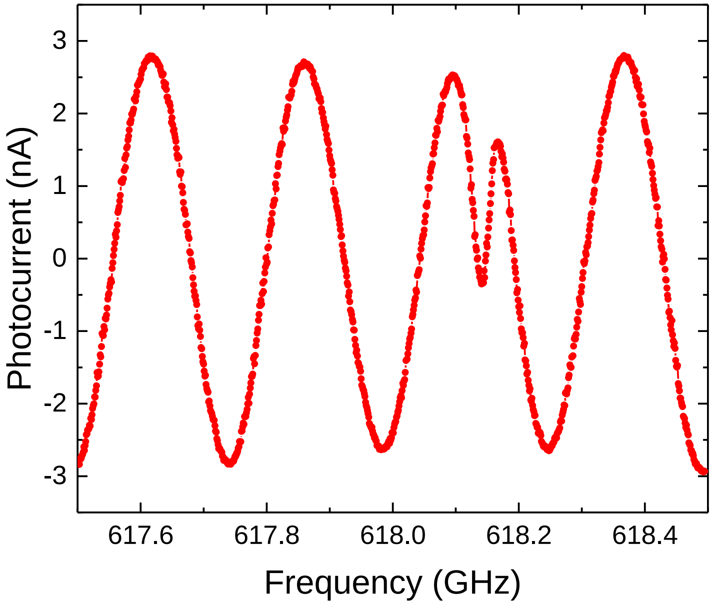
Combination of three DFB lasers, tuning range 600 GHz/laser

- Wavelength coverage from DC to 2.75 THz
- Excellent agreement between measured spectra and HITRAN data

A. Deninger et al., *J. Infrared Milli Terahz Waves* **36:3** (2015) 269.

TeraScan: Single-Megahertz Frequency Steps





Smallest step size: 1 MHz

- …corresponds to temperature intervals of 40 µK
- Step size approaches linewidth of DFB lasers

A. Deninger et al., *J. Infrared Milli Terahz Waves* **36:3** (2015) 269

D. Vogt et al., *J. Infrared Milli Terahz Waves* **40:5** (2019) 524

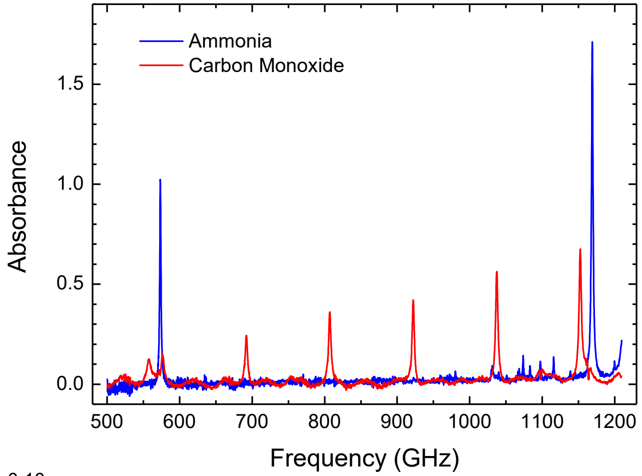
Application: Trace Gas Analysis

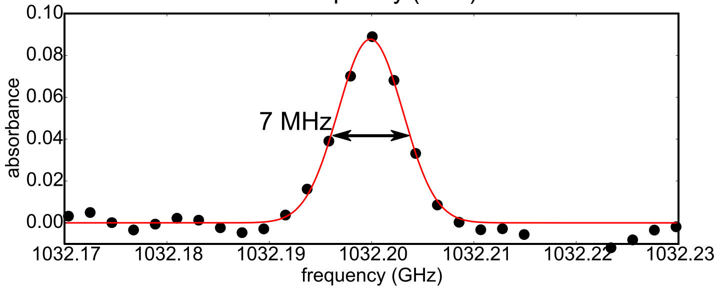
Goal: Identify hazardous gases

- Detect threatening chemicals in a “cluttered” background
- Minimize risk of false alarms (cleaning agents, perfumes, glue)

Solution: FD-THz spectroscopy

- A single spectroscopy system identifies a plurality of gases
- Even black smoke is transparent for THz radiation
- German national research project (2014-2017) involved the “Analytic Task Force” of fire brigade of Mannheim
- Measurements demonstrated ppm detection limits





Trace-gas sensing with ppm detection limits

C. Hepp et al., Proc. IRMMW-THz 2016

Application: Security

Goal: Identify hidden threats, e.g. in mail envelopes

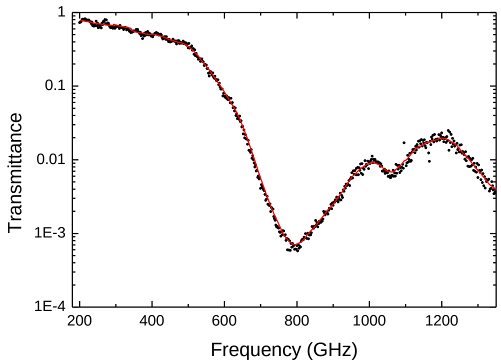
- Packaging materials like paper or cardboard are transparent @ THz frequencies
- Many explosives and illicit drugs exhibit characteristic absorption features

Solution: FD-THz imaging & spectroscopy

- Step 1: Generate image @ fixed frequency (flexibly chosen depending on sample)
- Step 2: If suspicious object is found, run spectrum to identify hazardous materials

Objects in mail envelope

M. Yahyapour et al., *IEEE Trans. THz Science Technol*. **6:5** (2016) 670



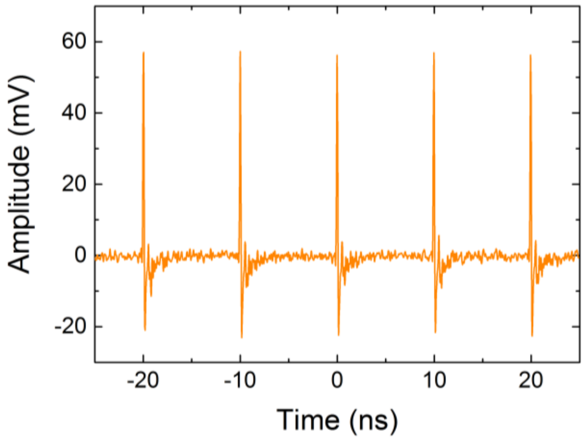
Plastic explosive RDX

A. Deninger et al., Proc. TeraTech, Osaka (2009)

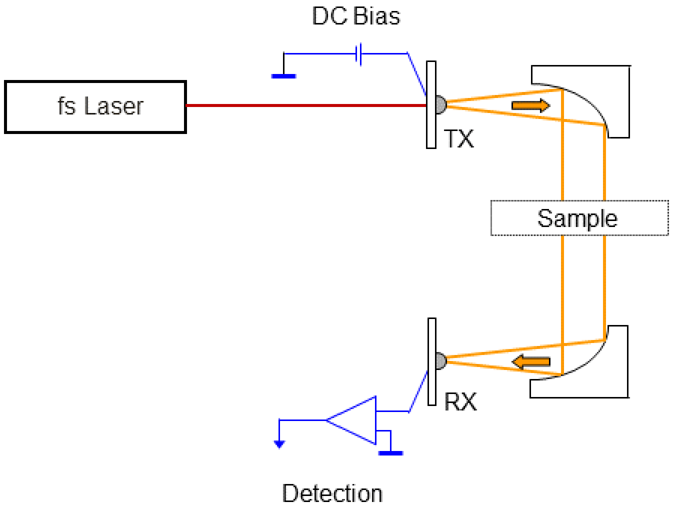
Terahertz Screening

Detection of Individual Terahertz Pulses

- Femtosecond laser produces 100 million pulses per second
- Fast Schottky receiver measures intensities of individual pulses
- No spectral information …
- … but pulse amplitude is measured with ns time resolution!
- → **10^5 .. 10^7 times faster** than conventional TD-THz systems



Pulse train @ 100 MHz repetition rate



F. Rettich et al., *J. Infrared Milli THz Waves* **36:7** (2015) 607
S. Brinkmann et al., *J. Infrared Milli. Terahz. Waves* **38:3** (2017) 339

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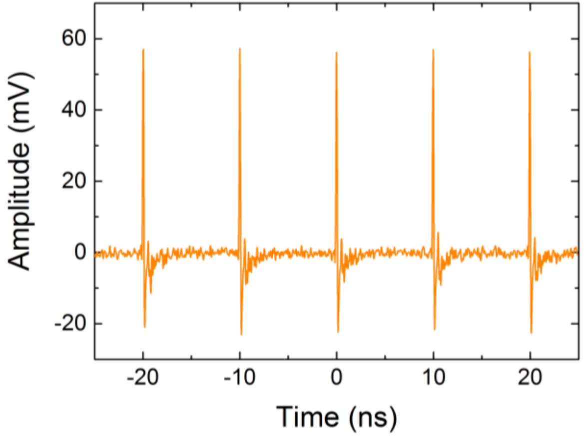

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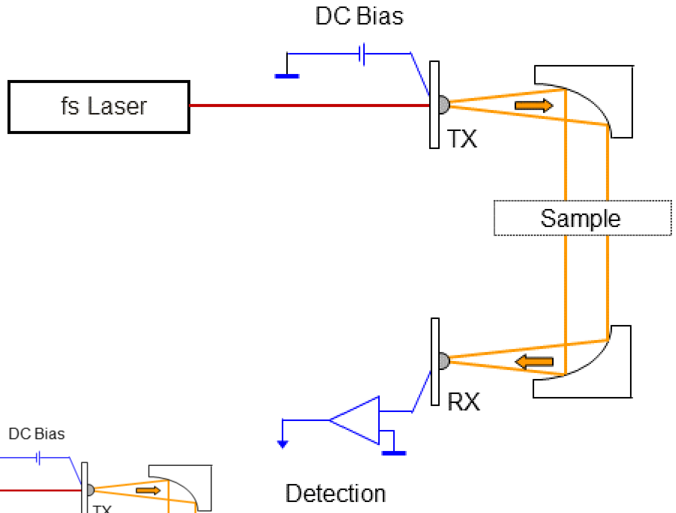
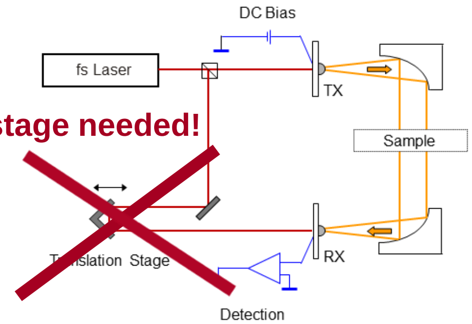
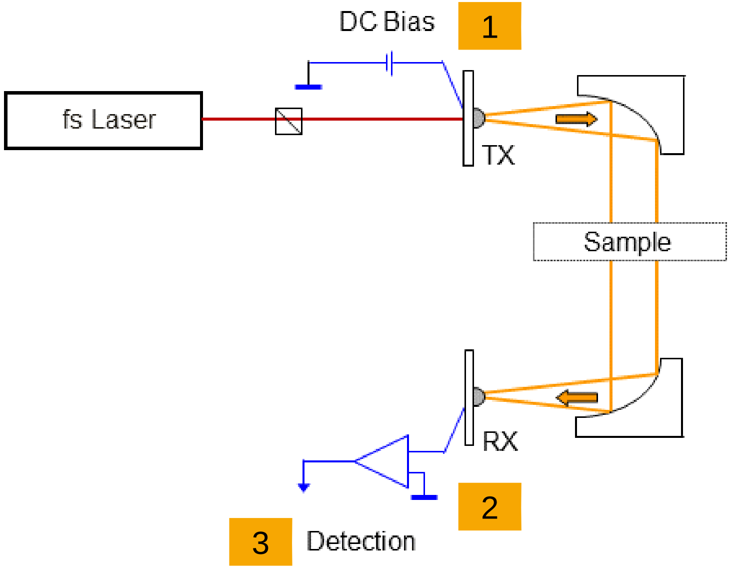


No delay stage needed!



F. Rettich et al., *J. Infrared Milli THz Waves* **36:7** (2015) 607
S. Brinkmann et al., *J. Infrared Milli. Terahz. Waves* **38:3** (2017) 339

TeraSpeed Components



TeraSpeed

1	TX: InGaAs photoconductive antenna (as for TDS systems)
2	RX: Fast Schottky diode with integrated amplifier, electric bandwidth = 4 GHz
3	Data acquisition + signal processing electronics

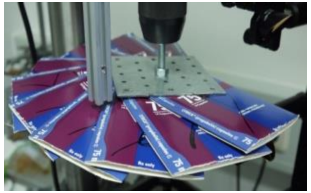
Application: Industrial Quality Control

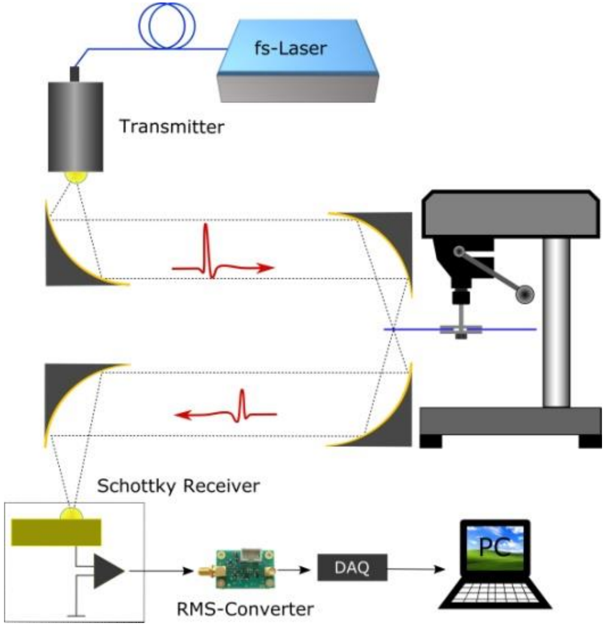
Task: Ensure that pharmaceutical packages include patient information leaflets

- EU legislation: “The inclusion in the packaging of all medicinal products of a package leaflet shall be obligatory […].”
- Present-day techniques: Weighing large batches of boxes → Integral values, missing insert cannot be localized
- But: Production line speed is several 10 m/s → data rates above 10 kHz required

Solution: Rapid THz screening

- Proof-of-principle: Samples mounted on turntable, velocities up to 21 m/s
- Samples rotate through terahertz beam
- Effective time resolution 6.4 µs, spatial resolution ~ 0.1 mm

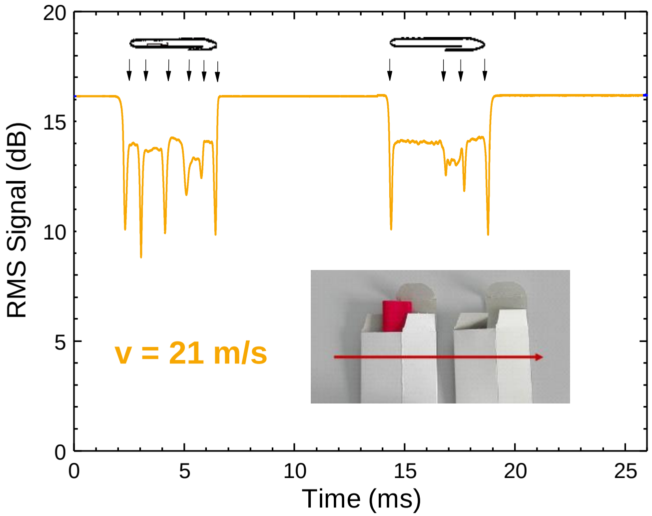




Application: Industrial Quality Control

Presence of inserts is detected unambiguously

- Distinctive signal pattern with and without inserts
- …even at velocities up to 21 m/s and up to 60% overlap of the packages



S. Brinkmann et al., *J. Infrared Milli THz Waves* **38** (2017) 339

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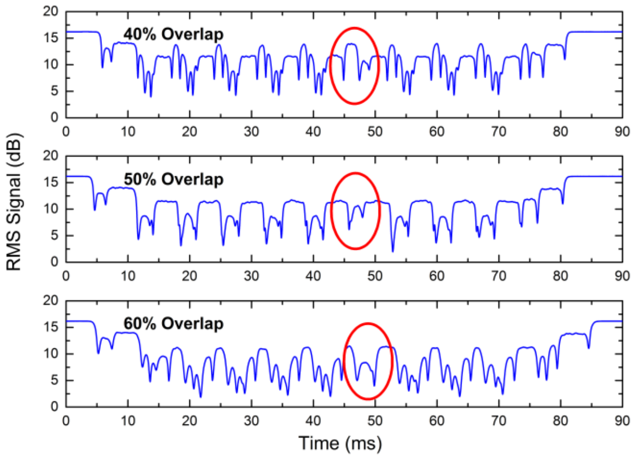
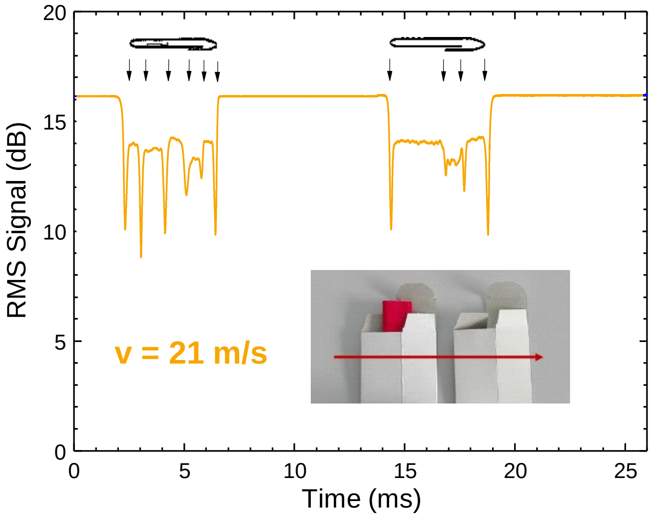
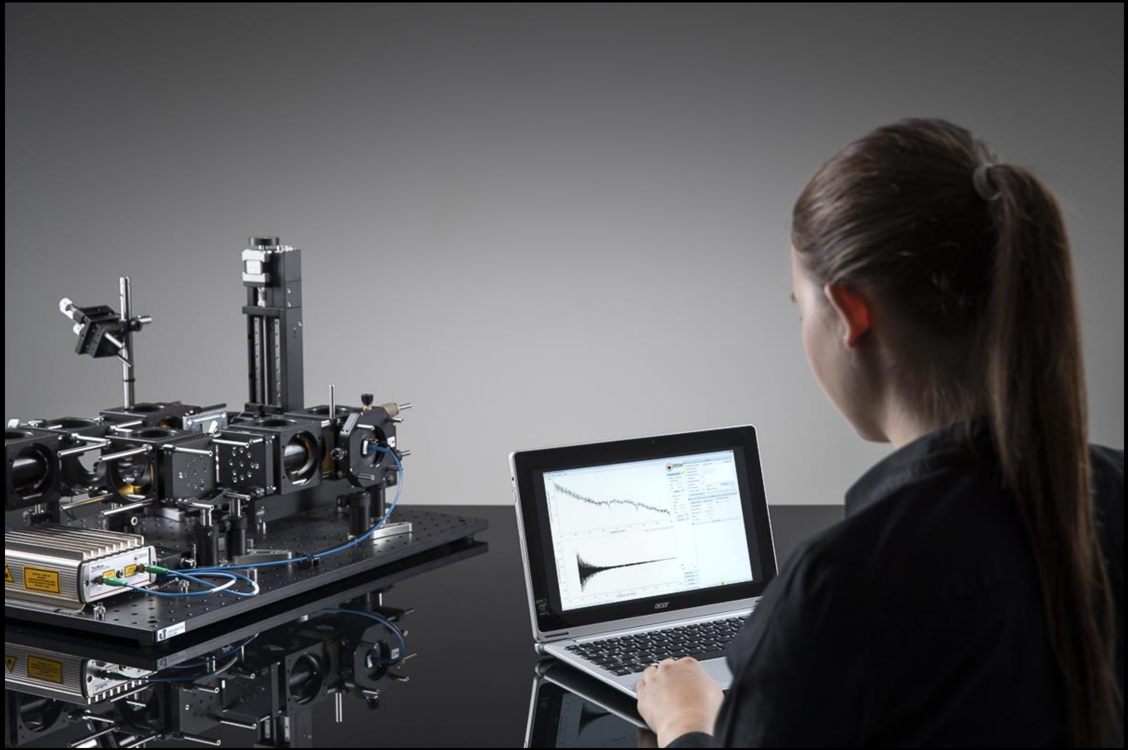


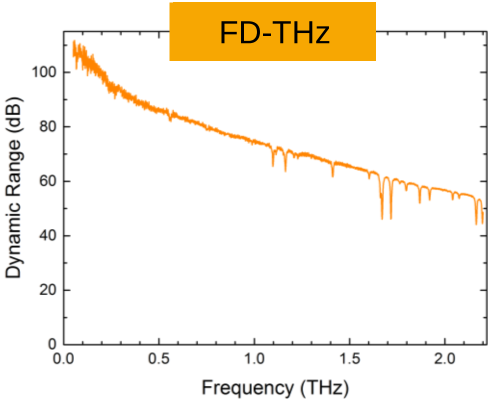


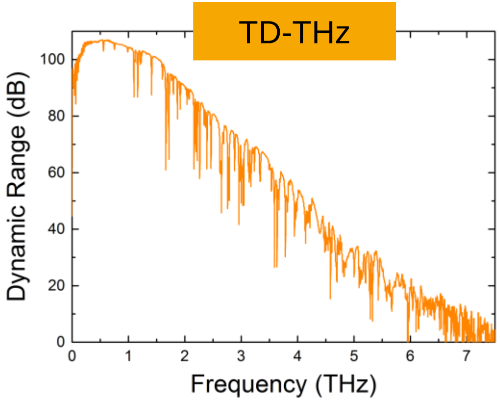
S. Brinkmann et al., *J. Infrared Milli THz Waves* **38** (2017) 339



Summary

Frequency-Domain vs. Time-Domain THz





Frequency-Domain (FD) vs. Time-Domain (TD) THz Spectroscopy		
	FD-THz	TD-THz
Bandwidth	0.05 – 2.7 THz, limited by laser	**0.1 – 6 THz**
Peak dynamic range	**~ 100 dB**	**~ 100 dB**
Frequency resolution	**1 MHz**	10 GHz typ.
Acquisition time (complete spectrum)	Minutes to hours, depends on resolution and lock-in time	**Milliseconds to 1 min.**, depends on pulse trace length and # averages
Spectral selectivity	**Yes**	No

Take-Home Message

Optoelectronic terahertz systems have matured significantly

- Progress in both laser and antenna technology

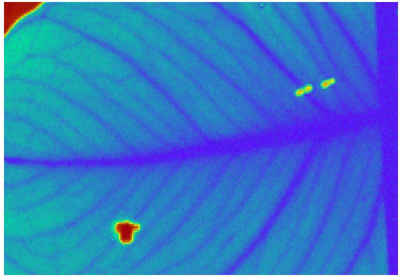
TD-THz: Delay stage concept determines measurement speed

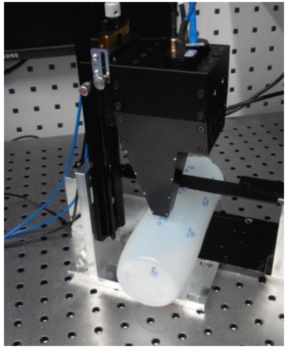
- Mechanical delay: slow but very precise
- Electronic delay: fast, less broad-band
- No delay: superfast without spectral information

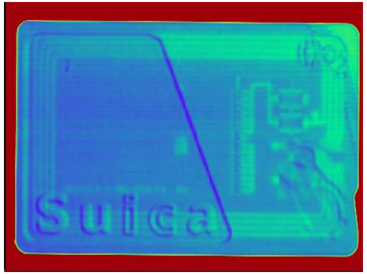
FD-THz: Extremely high frequency resolution

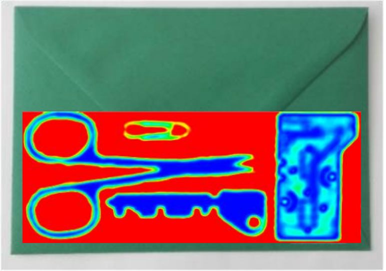
- Single-MHz demonstrated – 3 orders of magnitude higher than pulsed systems

Number of applications is growing continuously.









Collaboration Partners

Collaboration Partners:

TOPTICA Photonics AG

Simeon Brinkmann, Katja Dutzi, Nico Vieweg, Axel Roggenbuck, Milad Yahyapour, Anselm Deninger

Fraunhofer Heinrich-Hertz Institute, Berlin

Björn Globisch, Robert Kohlhaas, Lars Liebermeister, Simon Nellen, Helmut Roehle

Papiertechnische Stiftung Heidenau

Gerhard Gärtner, Patrick Plew

Backup Slides

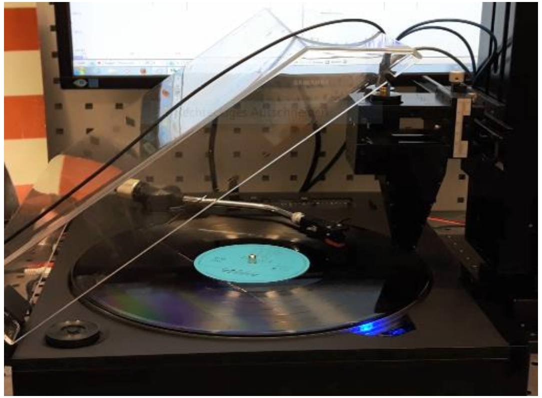
Layer Measurements on Moving Samples

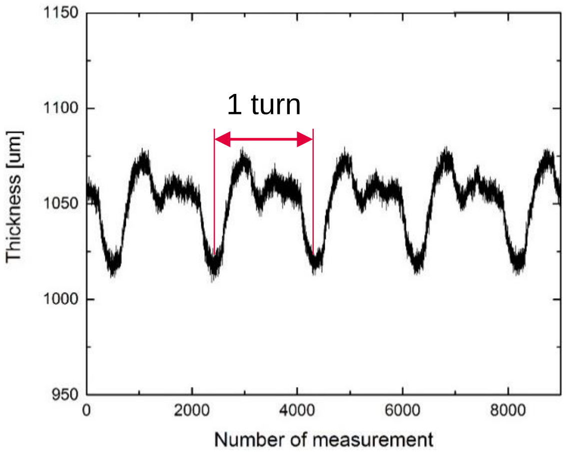
Measurement speed matters…

- Moving samples: e.g. conveyor belts, extrusion lines, …
- “One-hundred-percent” inspection often requires kHz measurement rates

Proof-of-principle measurement

- Thickness measurement of rotating vinyl record
- Approx. 0.7 m/s
- Measurement speed: 1600 terahertz traces/s (with ECOPS)
- → Thickness gauging resolves inhomogeneities on the order of 60 µm





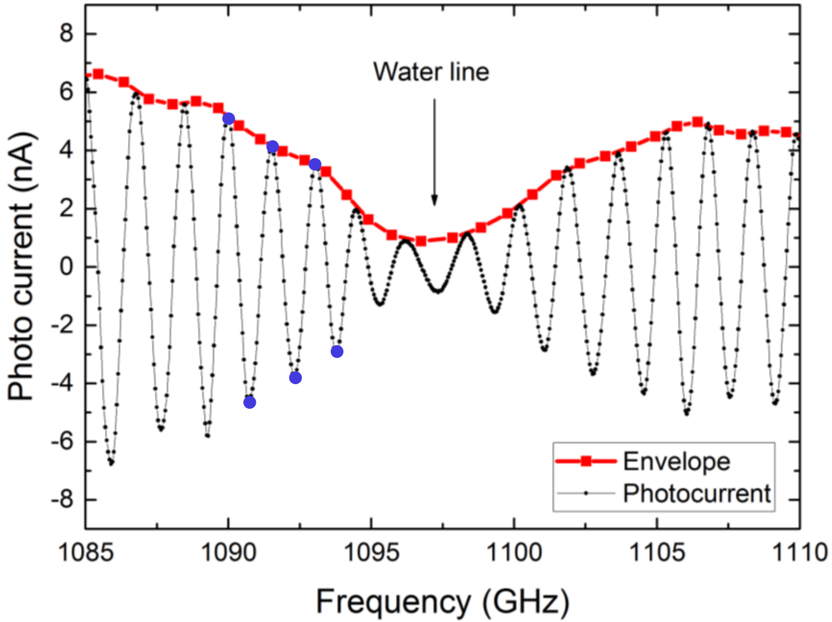
TOPTICA PHOTONICS

cw-Terahertz Data Analysis

- Envelope of detected photocurrent represents terahertz electric field amplitude

$$I_{RX}(\nu) \propto E_{THz}(\nu) \cdot \cos(2\pi \cdot \Delta L \cdot \nu / c)$$

- I_{RX} Receiver photocurrent
- E_{THz} THz electric field
- ΔL Path length difference to RX
- ν THz frequency
- c Speed of light



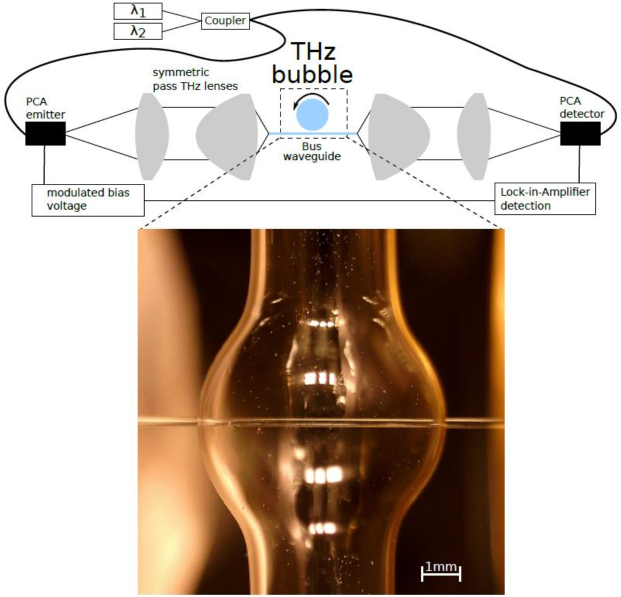
Application: High-Resolution Spectroscopy – WGM Resonators

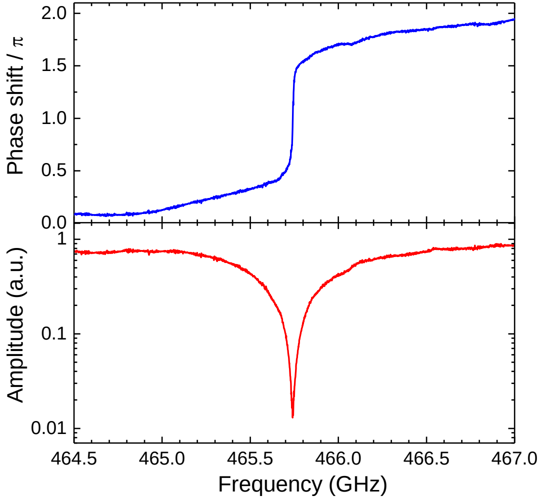
Goal: Characterize high-Q resonators

- Potential for chemical / biological sensing, since resonance lines change when samples are “loaded”
- Whispering gallery mode resonators (quartz or silicon) exhibit particularly narrow lines

Solution: FD-THz spectroscopy

- THz spectroscopy resolves higher-order radial modes, Fano resonances, …
- Present record: Q factor of 22000 (Univ. of Auckland, New Zealand)

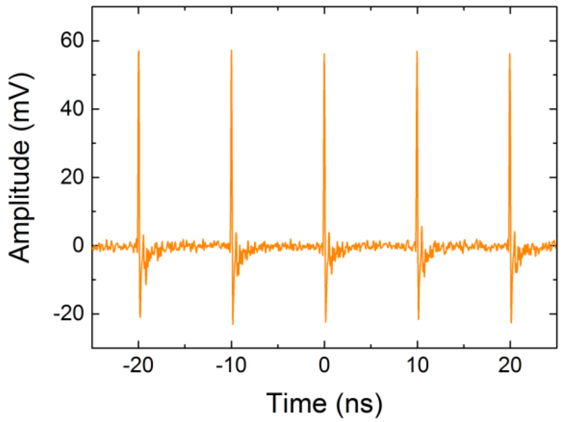




D.W. Vogt et al., *Opt. Express* **25:14** (2017) 16860
D.W. Vogt et al., *Opt. Lett.* **22:21** (2017) 4359
D.W. Vogt et al., *Opt. Express* **26:24** (2018) 31190

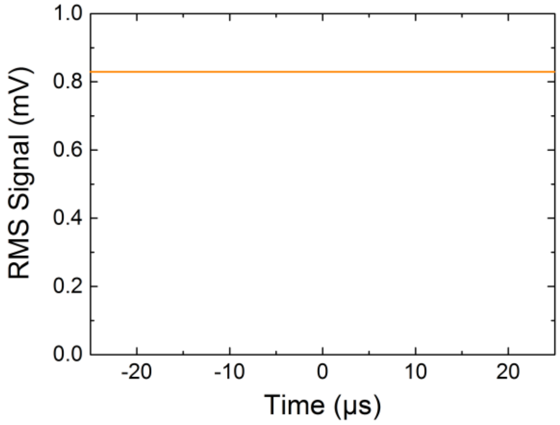
Signal Processing

Analog output: Raw signal



RF-to-RMS converter

Digital output: RMS signal



- Handling 100 MHz data streams is tough…
  → RF-to-RMS converter processes signals (and reduces bandwidth)
- Digital output: RMS signal, max. 500 kHz sampling rate (slower is possible)
- Analog output: Original 100 MHz pulse train

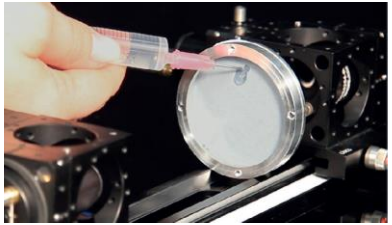
Application: Ultrafast Dynamics

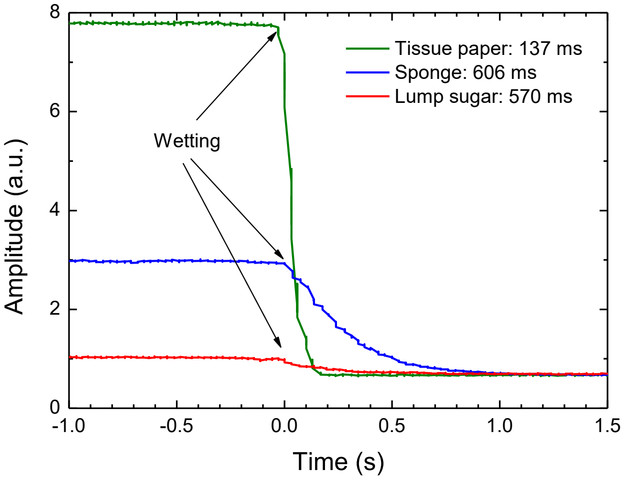
Goal: Observe dynamic processes with high temporal resolution

- Protein dynamics, unfolding of biomolecules: time scales of ms .. µs

Solution: High-speed transmission measurements

- Proof-of-principle: Assess spreading of water droplet in three different materials
- Water reduces THz signal as it spreads
- Sub-second time wetting dynamics resolved





Wetting dynamics (with 90% : 10% time constants)

F. Rettich et al., *J. Infrared Milli THz Waves* **36:7** (2015) 607

Application: Curing of Glue

Goal: Understand the curing process of adhesives

- Optimize material composition and/or curing parameters

Solution: High-speed transmission measurements

- Proof-of-principle: Adhesives placed in the THz beam focus
- Curing via 2-component mixing or UV illumination
- Transmission monitored with 0.5 s time resolution
- Curing initially exothermic, temperature increase reduces transmission
- Transmission increases again as glue hardens; “curing point” reached once signal change >98% of final state
- Curing time depends on layer thickness