Continuous-Wave Terahertz Systems

Operation Principle, System Configurations & Accessories

TOPTICA Photonics AG

All Wavelengths.
190 nm - 0.1 THz

What is terahertz radiation?

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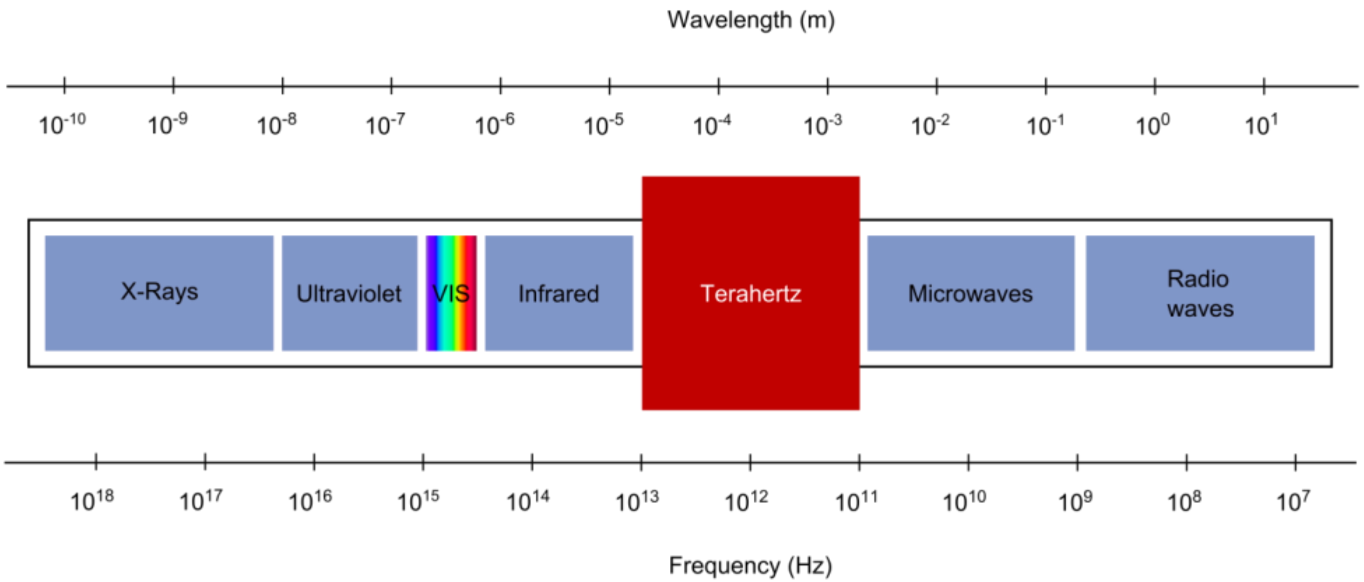

- 1 THz ↔ 33 cm^{-1} ↔ 300 µm ↔ 4.1 meV
- Plastic, paper, cardboard, … transparent to THz waves → **Imaging**
- Many gases and organic solids show THz “fingerprints“ → **Spectroscopy**
- Non-ionizing – no health hazards

Product highlights

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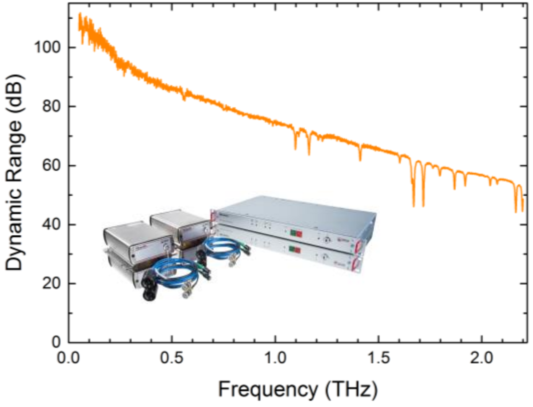
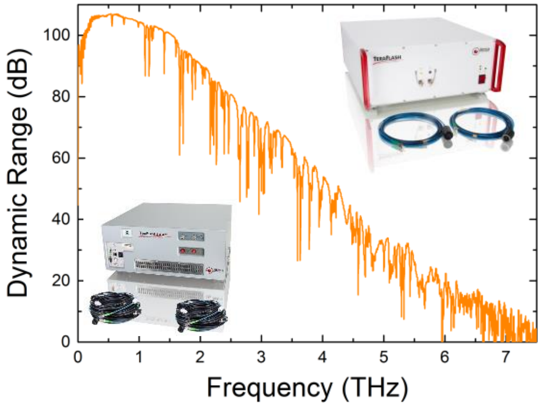
Frequency-domain platforms



TopSeller: TeraScan

- Tunable DFB lasers
- Fiber-coupled terahertz antennas
- < 10 MHz resolution
- up to 100 dB dynamic range

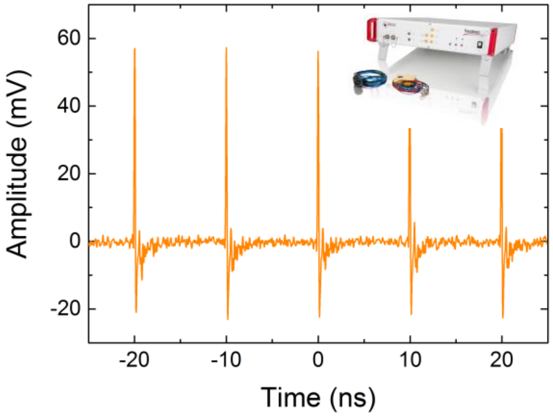
Time-domain platforms



TopSellers: TeraFlash pro & smart

- Robust ultrafast fiber lasers
- Fiber-coupled terahertz antennas
- TF pro: 6 THz bandwidth, 95 dB PDR
- TF smart: > 4 THz, 1600 pulse traces/s

Superfast screening platform



TopSeller: TeraSpeed

- Robust ultrafast fiber lasers
- Photoconductive emitter + high-bandwidth Schottky receiver
- 500 kS/s (digital), 100 MS/s (analog)

Frequency-domain vs. time-domain THz

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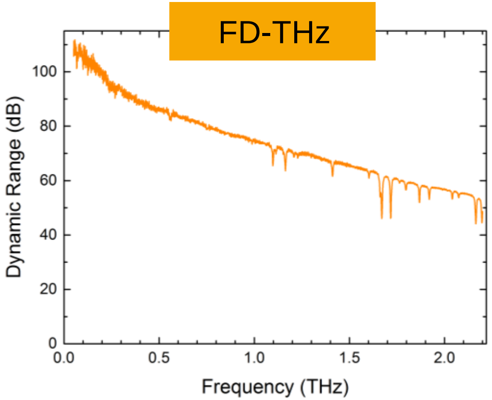

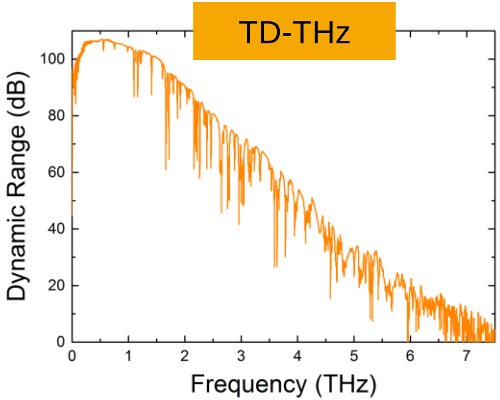

Frequency-Domain (FD) vs. Time-Domain (TD) THz Spectroscopy		
	FD-THz	TD-THz
Bandwidth	0.05 – 2.7 THz, limited by laser	**0.1 – 6 THz**
Peak dynamic range	**~ 100 dB**	**~ 100 dB**
Frequency resolution	**10 MHz**	10 GHz typ.
Acquisition time (complete spectrum)	Minutes to hours, depends on resolution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

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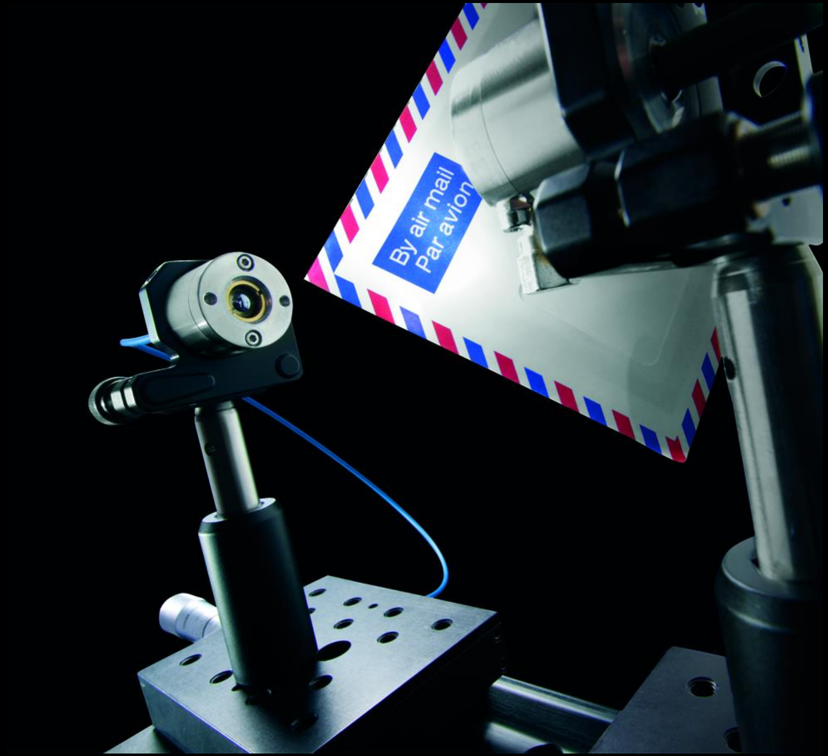
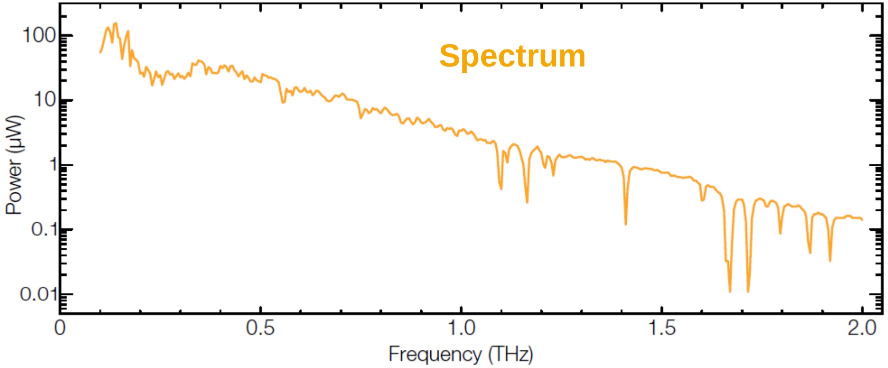
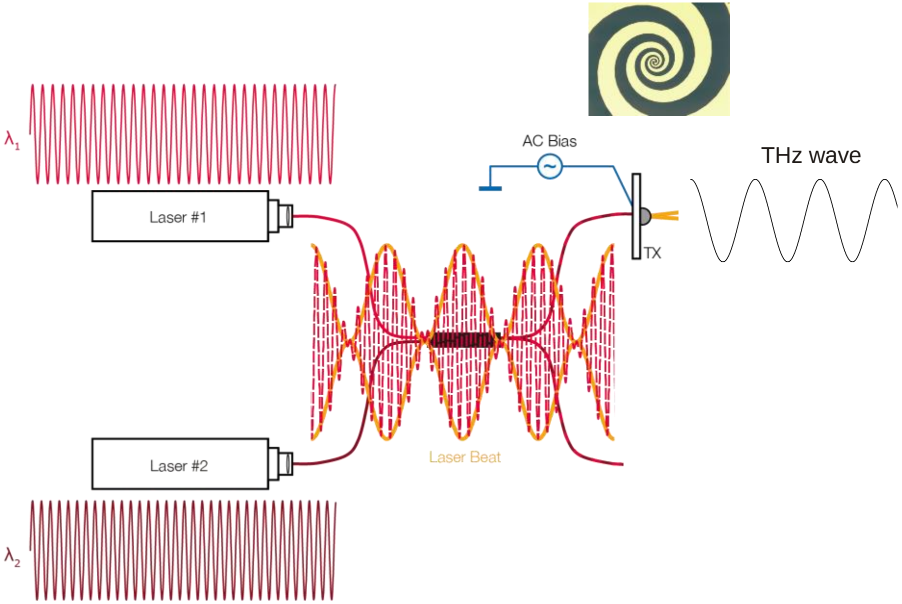


Frequency-domain terahertz generation & detection

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





Frequency-domain terahertz detection

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- 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)

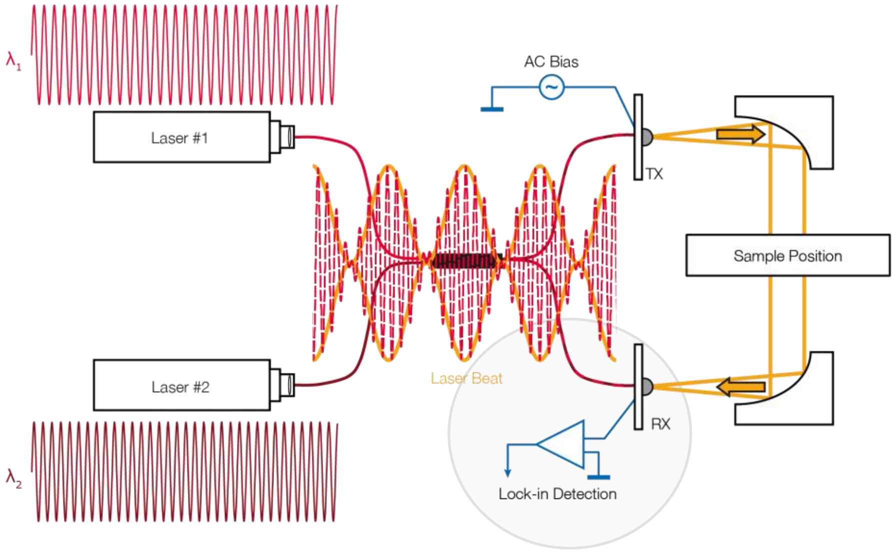
Proportional to THz electric field

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

Lock-in detection:

- Short integration time ⬄ high measurement speed (~ 30 s / spectrum)
- Long integration time ⬄ lower noise floor

Coherent signal detection



Coherent signal detection (I)

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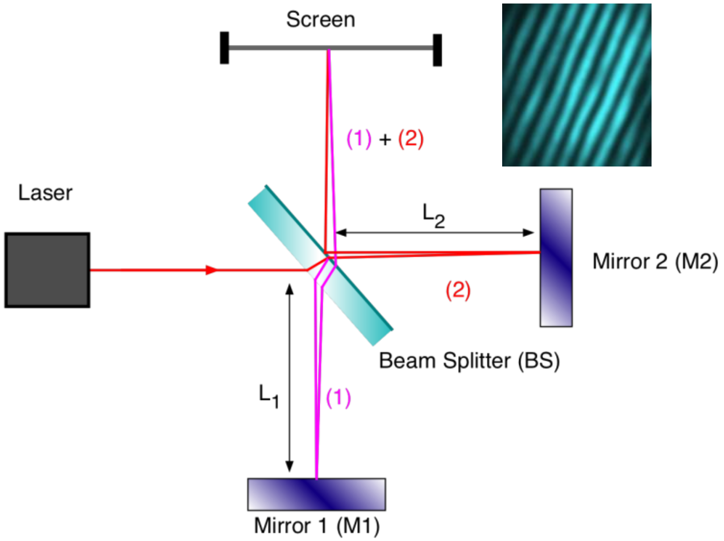
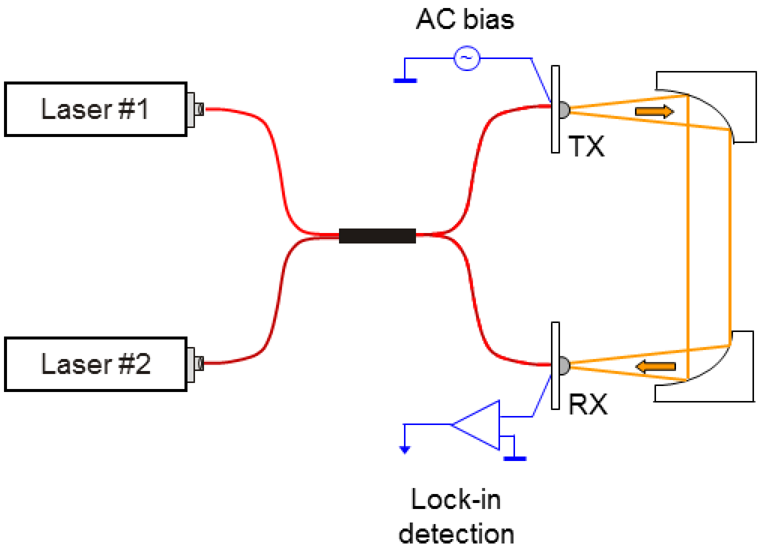
Michelson interferometer



Changing the arm length or the laser frequency “moves“ fringes.

cw THz setup



Fiber-optic splitter creates two beam paths.

RX is reference plane.

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Coherent signal detection (II)

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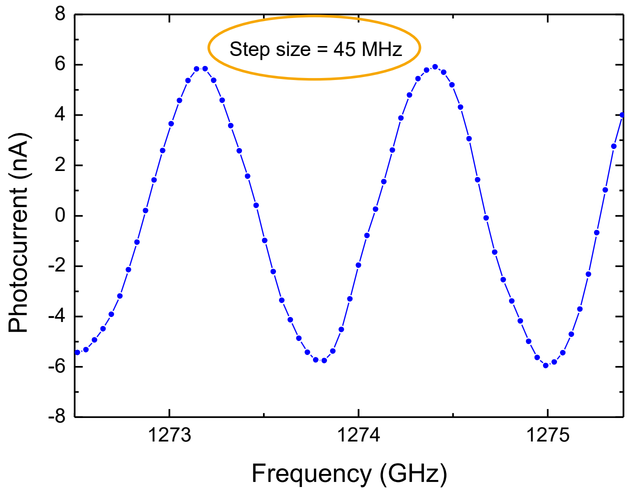
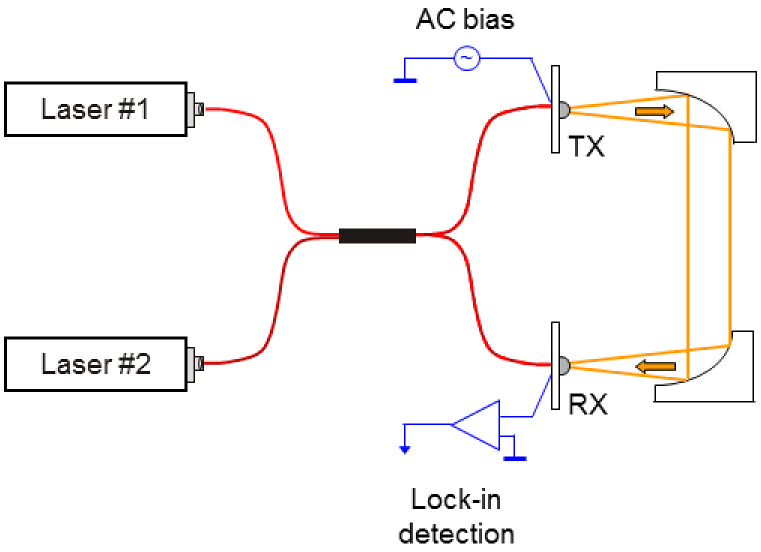
Laser temperature change: 1 mK



cw THz setup



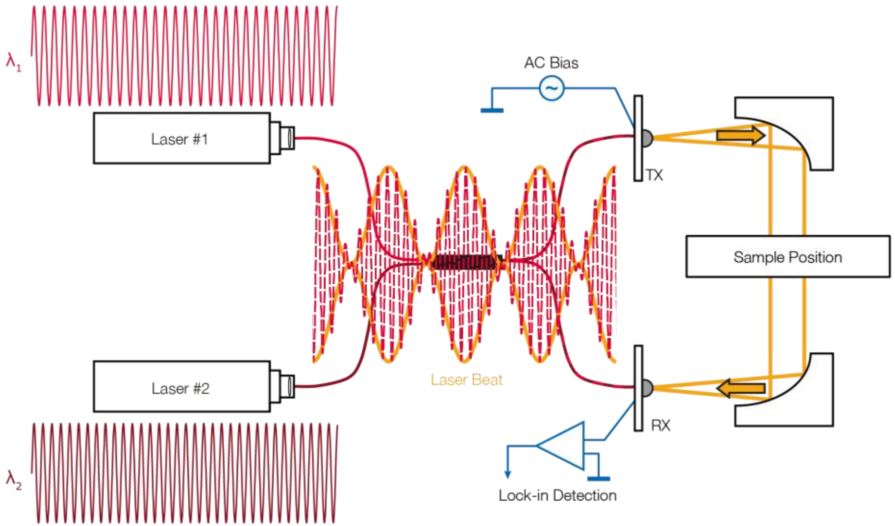
- No moving parts → cost-effective
- Detection of THz amplitude and phase
- Highly efficient: Dynamic range ~ 100 dB even though P_{THz} ~ 100 µW

Coherent signal detection (III)

- Detected photocurrent:

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

- With:
  - I_{RX} = receiver photocurrent
  - E_{THz} = THz electric field
  - ΔL = path length difference to RX= | $L_1 - L_2$ |
  - ν = THz frequency
  - c = Speed of light
- L_1 begins at beam splitter, continues to TX, includes THz path and terminates at RX
- L_2 begins at beam splitter and terminates at RX



Data analysis – terahertz amplitude spectrum

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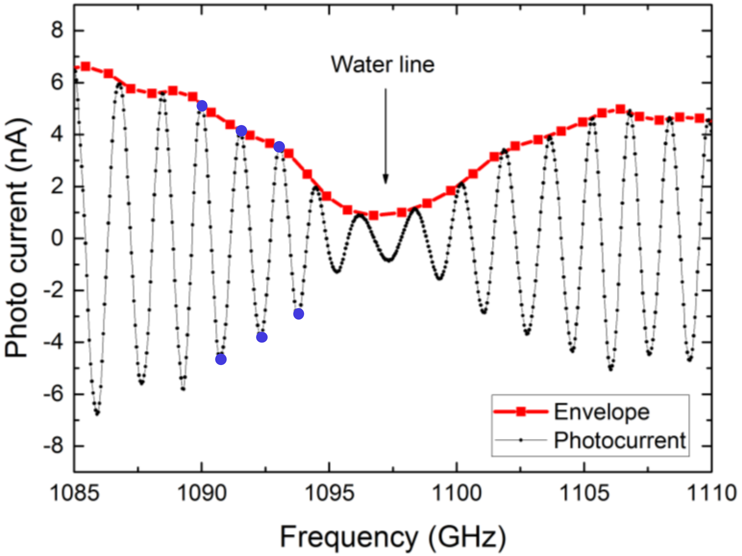
- Amplitude of the terahertz electric field is the envelope of detected photocurrent:

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



- Determination of the envelope with TeraScan Software:

Maxima and minima are evaluated and adjacent values averaged.

$$Envelope\left(\frac{1}{2}|\nu_{Max} - \nu_{Min}|\right) = \frac{1}{2}(|E_{THz}(\nu_{Max})| + |E_{THz}(\nu_{Min})|)$$

with:

- $\nu_{Max\,/Min}$ = THz frequency at photocurrent max. / min.

Fringe spacing

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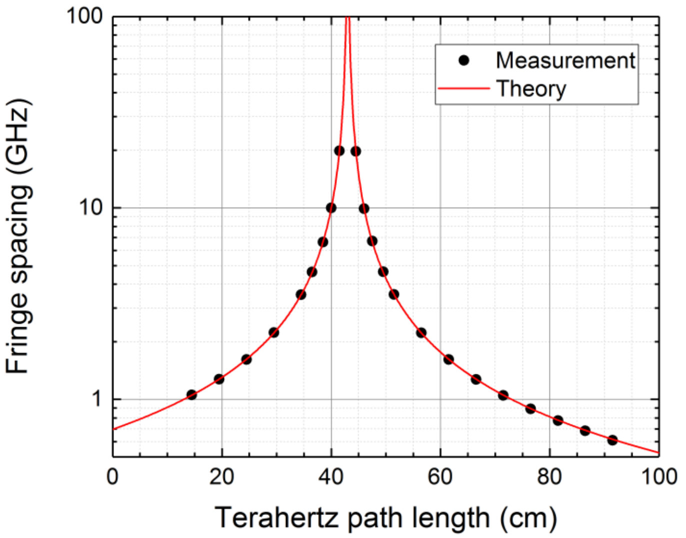
- Fringe spacing is inversely proportional to terahertz path length:

  $$\Delta\nu = c/\Delta L$$

  - $\Delta\nu$ Fringe spacing (interval between two phase maxima)
  - c Speed of light
  - ΔL Path length difference to RX

- RX fiber is 30 cm longer than TX fiber → extra optical path ~ 43 cm
- Consequently, terahertz path length of ~ 43 cm corresponds to $\Delta L = 0$
- Fringe spacing of 2-3 GHz ⇔ path length between 28-33 cm or 53-58 cm

  (values may slightly differ due to production tolerances)



Note: Path length is measured from/to virtual focus point, i.e. includes sections within the photomixers (see "back focus distance" in datasheet).

Dynamic range and noise level

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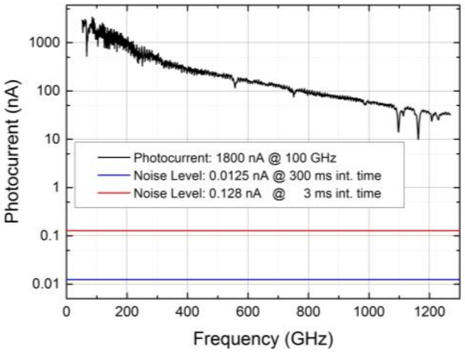

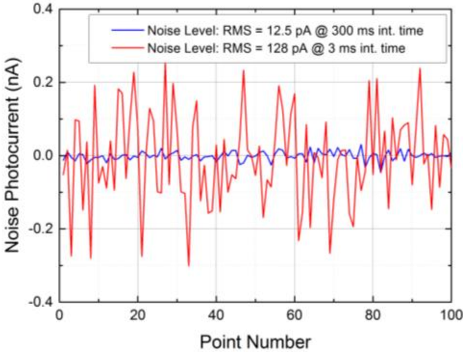

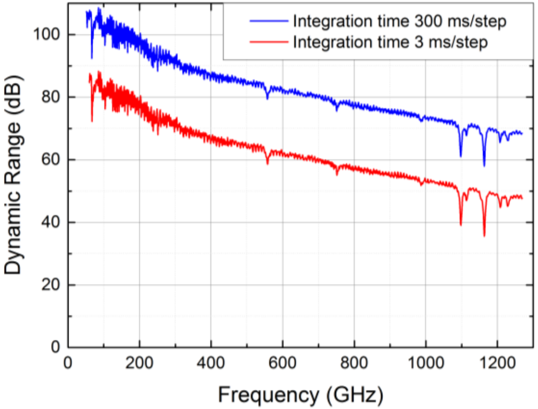

- Dynamic range (DR):

  $DR(\nu) = 20 \cdot \log(I_{signal}/I_{noise})$

- I_{signal} – Photocurrent in THz receiver:
  - depends on frequency
  - independent of lock-in integration time

- I_{noise} - Noise level:
  - intrinsic property of the photomixer, depends on optical power on the receiver
  - Lock-In-Detection: $I_{noise} \propto 1/\sqrt{integration\ time}$
  - RMS measurement without terahertz radiation

Single-megahertz frequency steps

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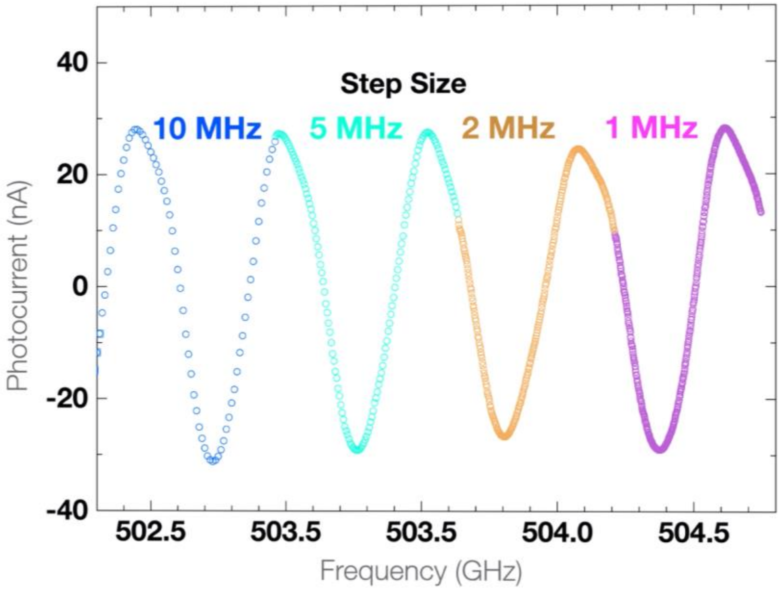
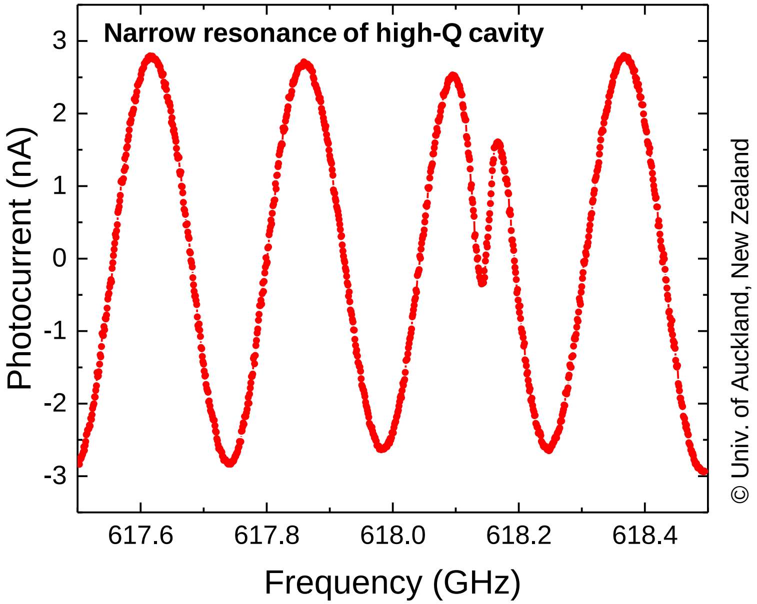




Smallest step size: 1 MHz

- …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

TeraScan

TeraScan 1550

TeraScan 780

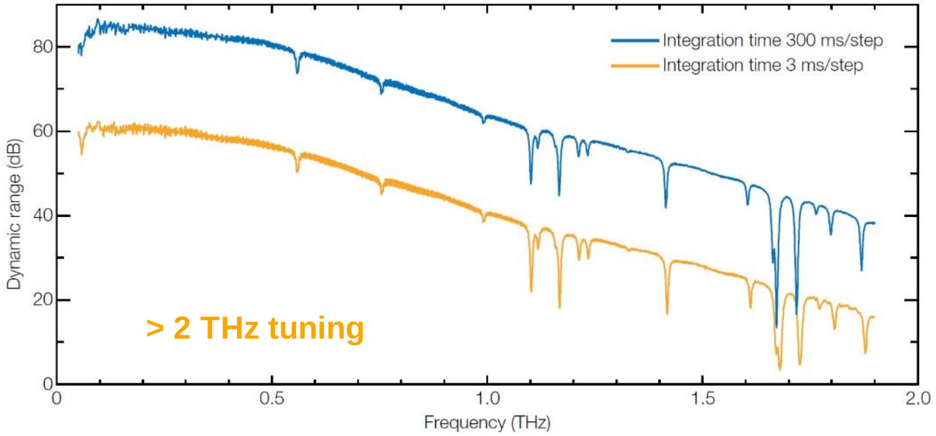
TeraBeam

Tuning Range Extension

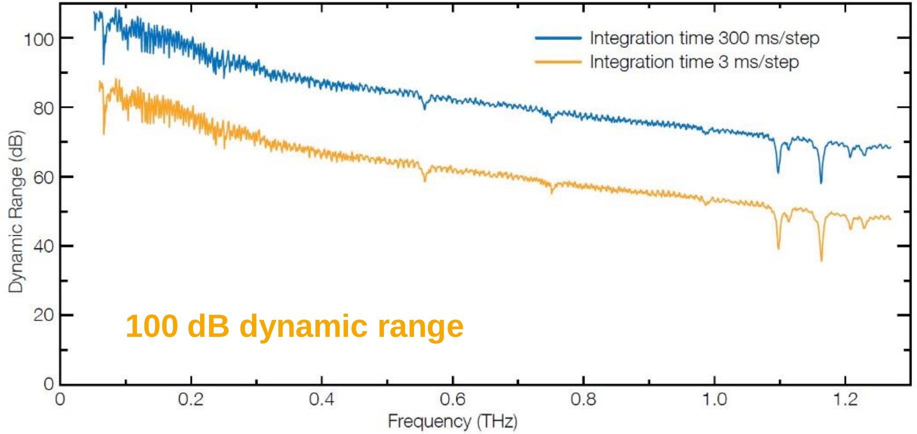
Phase Modulation Extension

GaAs and InGaAs Photomixers

TeraScan 780 and TeraScan 1550



> 2 THz tuning



100 dB dynamic range

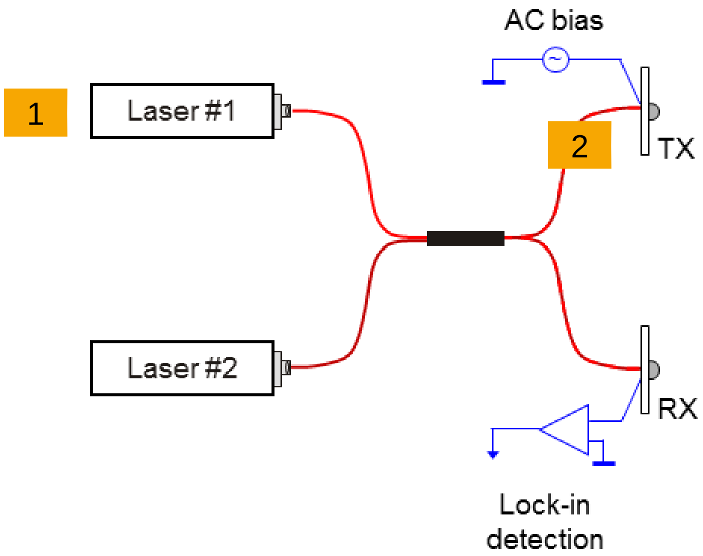
TeraScan 780

TeraScan 1550

Pre-configured systems

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

TeraScan components



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

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

DFB pro diode lasers

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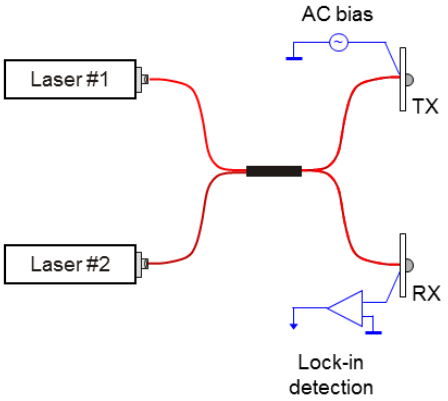
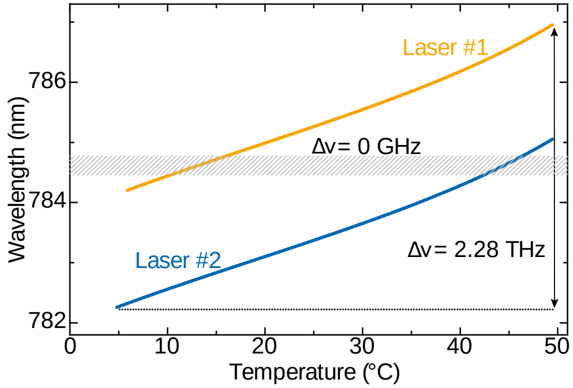




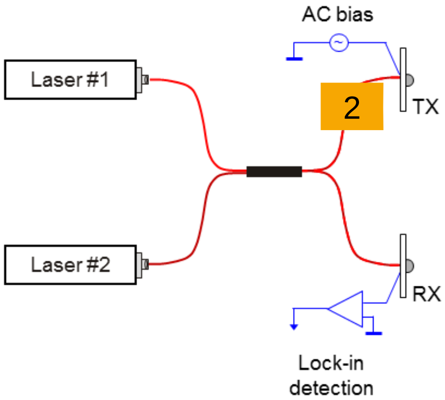
Tunable DFB pro lasers

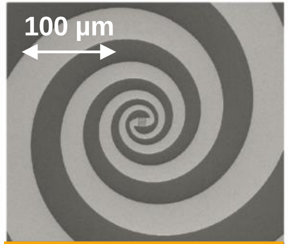
- 2 DFB diodes: λ ~ 0.8 µm or λ ~ 1.5 µm
- Computerized frequency control via precise calibration
- Bandwidth 0 – 2 THz (@ 780 nm)
- Fiber-optic beam combination

DFB pro advantages

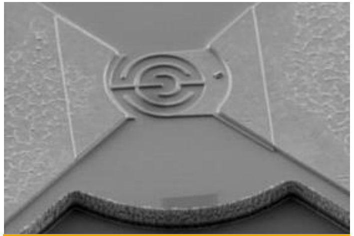
- Compact, stable lasers
- Temperature accuracy < 50 µK ↔ excellent frequency resolution
- Customized frequency ranges u.r.

Photomixers





GaAs-based photomixer



InGaAs-based photomixer

Photomixer = Fast semiconductor + antenna

- GaAs: 0.8 µm → widest tuning range of DFBs
- InGaAs: 1.5 µm → maximum dynamic range
- Max. power ~ 100 µW (InGaAs @ 100 GHz)
- Peak dynamic range > 90 dB (> 100 dB typ.)

Advantages of TOPTICA‘s photomixers

- Long-standing partnerships with world-leading manufacturers
- Highest dynamic range of any commercial cw-THz system
- Packaged, fiber-pigtailed modules

Control electronics DLC smart

Control unit: DLC smart

- Digital control electronics with Ethernet interface
- 75% smaller footprint, 50% less weight, compared to previous version
- Improved frequency accuracy due to real-time temperature measurement
- Control unit “recognizes“ laser heads connected
- System can be part of a computer network → convenient remote control

Modular product packages

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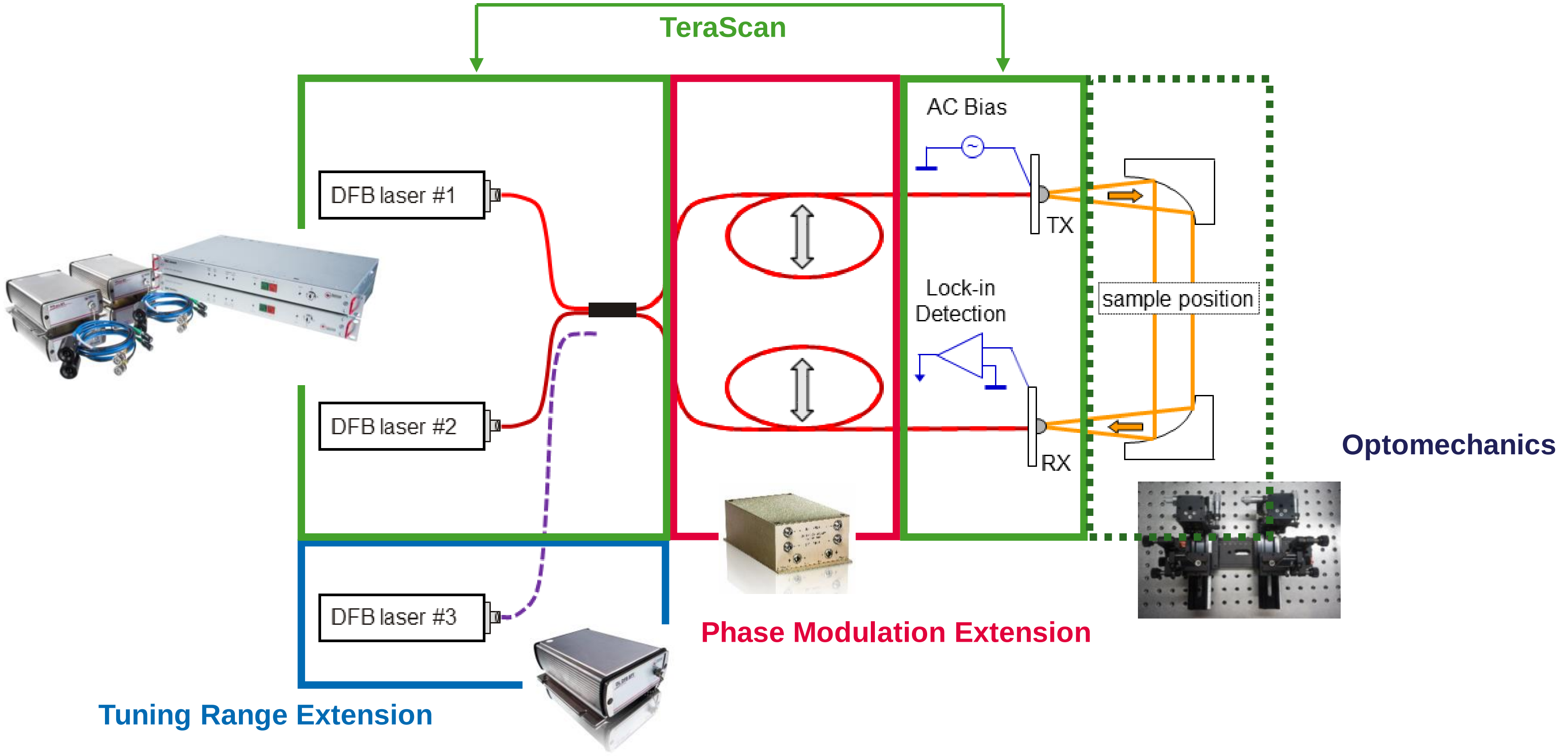

Tuning Range Extension

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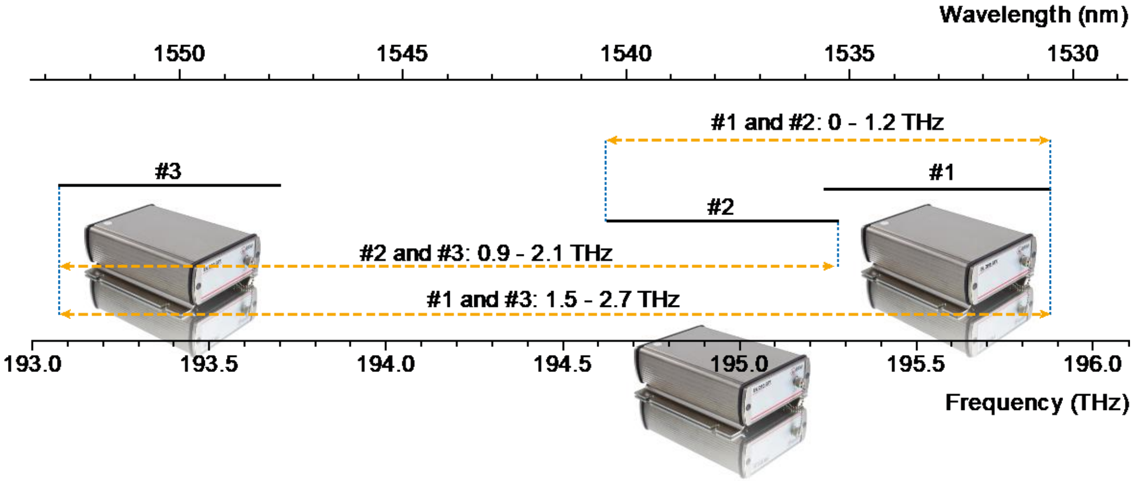

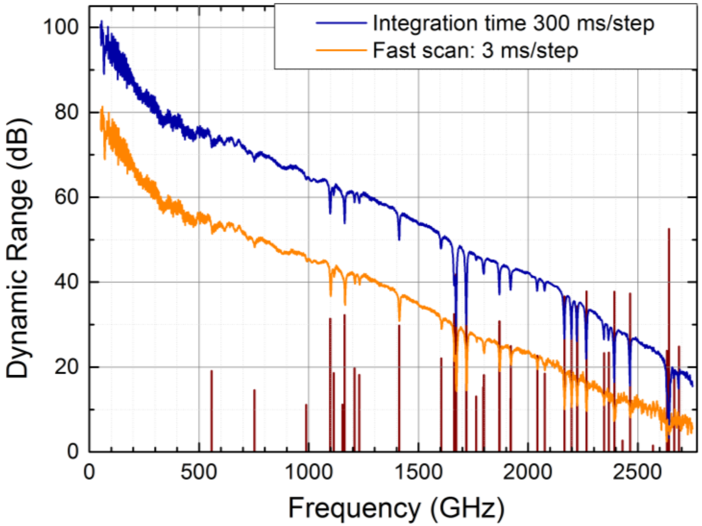

Combination of three DFB lasers, tuning range 600 GHz/laser

- 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.

Phase Modulation Extension

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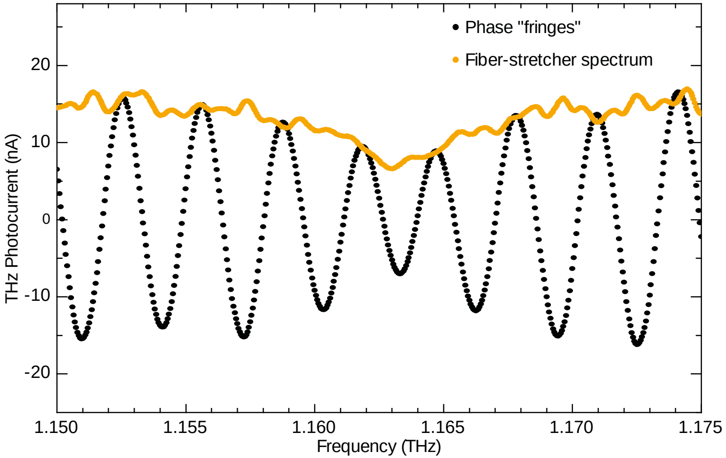
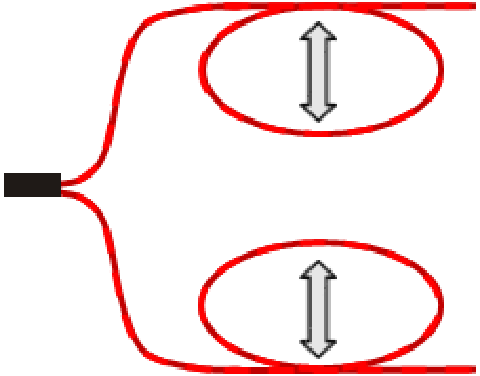
“Resolution Booster“: Phase and amplitude information @ <10 MHz resolution

- Standard configuration: Spectral resolution depends on phase “fringes”, typical resolution ~ 1 GHz (black symbols in figure)
- Phase modulation extension measures **envelope** of fringes (yellow trace in fig.)
- Technology: 2 fiber stretchers for path length modulation (up to 3 mm @ 1 kHz)
- Twin fiber concept provides enhanced thermal stability





A. Roggenbuck et al., *J. Opt. Soc. Am. B* ***29*** *(2012) 614*

TeraScan specifications

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	TeraScan 780	TeraScan 1550
“In a nutshell”	**Wide scan range**	**High power**
Optical wavelength	780 nm	1550 nm
Semiconductor material	GaAs	InGaAs on InP
Emitter/Receiver (Article codes)	2 x photomixer (#EK-000831 / #EK-000832)	High-speed PD / photomixer (#EK-000724 / #EK-000725)
Scan range	**0 – 1.8 THz (typ. > 2 THz), without changing lasers**	0 – 1.2 THz Up to 2.7 THz with 3 lasers
THz power	Typ. 2 µW @ 100 GHz, 0.3 µW @ 500 GHz	**100 µW @ 100 GHz, 10 µW @ 10 GHz**
Dynamic range @ 300 ms integr. time	> 80 dB @ 100 GHz **> 70 dB (typ. 80 dB) @ 500 GHz Typ. 70 dB @ 1000 GHz**	**> 90 dB (typ. 100 dB) @ 100 GHz > 70 dB (typ. 80 dB) @ 500 GHz Typ. 70 dB @ 1000 GHz**
Polarization	**Circular, ~ 30 dB PER**	Linear, ~ 10 dB PER
Frequency accuracy	< 2 GHz	
Minimum step size	**< 10 MHz**	

Optomechanics

Schottky Diodes

Accessories

Terahertz optomechanics (I)

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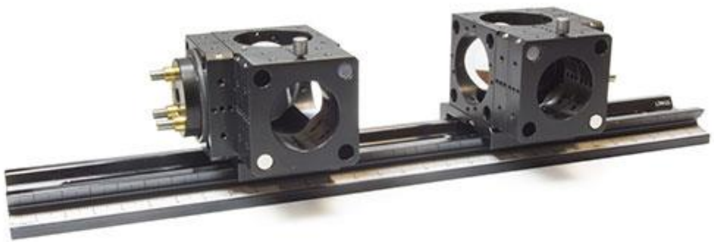

#BG-002653: Compact rail setup

#OE-000888: Reflection head

- Compact + robust setups
- Rail with 2 mirrors for transmission measurements
- Reflection head with 4 mirrors → beam focus at sample location

Terahertz optomechanics (II)

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#BG-001481: Two mirrors, collimated beam

#BG-001784: Four mirrors, additional focus

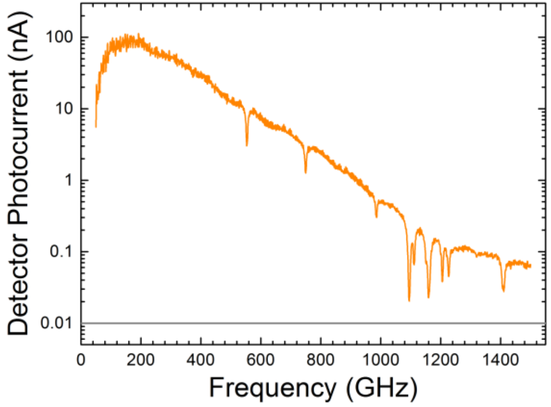
- Flexible solutions for transmission measurements
- Precise 3-axis-stages for THz antennas
- Two mirrors: Collimated beam
- Four mirrors: Additional beam focus

Optomechanics specifications

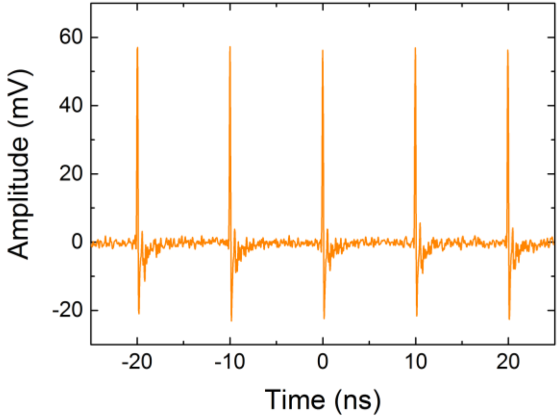
Optomechanics: Specifications				
	#BG-002653 (compact rail)	#BG-001481 (2-mirror setup)	#BG-001784 (4-mirror setup)	#OE-000888 (Reflection head)
User mode	Transmission	Transmission	Transmission	Reflection
Collimating mirrors	∅ 1“, focal length 2“	∅ 2“, focal length 3“	∅ 2“, focal length 3“	∅ 1“, focal length 2“
Focussing mirrors	**--**	--	∅ 2“, focal length 2“	∅ 1“, focal length 4“
Focus size	**--**	--	~ 2 mm	~ 3 mm




Schottky diodes



“High-responsivity“ model #EK-000933:
Broadband spectrum with GaAs emitter



“High-bandwidth“ model #EK-000961:
Detection of individual THz pulses

Schottky receiver: Incoherent detection scheme

- Output signal proportional to THz power, no phase relation with transmitter
- Suitable for spectroscopy, ideal for THz imaging
- Two versions with different amplifier bandwidth available

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

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

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

Schottky diodes specifications

Schottky diodes: Specifications		
	#EK-000933 (“High Responsivity“)	#EK-000961 (“High Bandwidth“)
Concept	Zero-bias Schottky diode	
Terahertz bandwidth	50 – 1500 GHz	
Noise-equivalent power	7 pW/sqrt(Hz) @ 100 GHz 100 pW/sqrt(Hz) @ 1000 GHz	70 pW/sqrt(Hz) @ 100 GHz 1000 pW/sqrt(Hz) @ 1000 GHz
Typ. responsivity	22000 V/W @ 100 GHz 1100 V/W @ 1000 GHz	230 V/W @ 100 GHz 17 V/W @ 1000 GHz
Amplifier bandwidth	10 Hz – 1 MHz	10 MHz – 4 GHz
Applications	Imaging, Spectroscopy	Imaging, THz-based communication, ultrafast dynamic processes