THz Equipment: State of the Art and Requirements for Next Generation Devices

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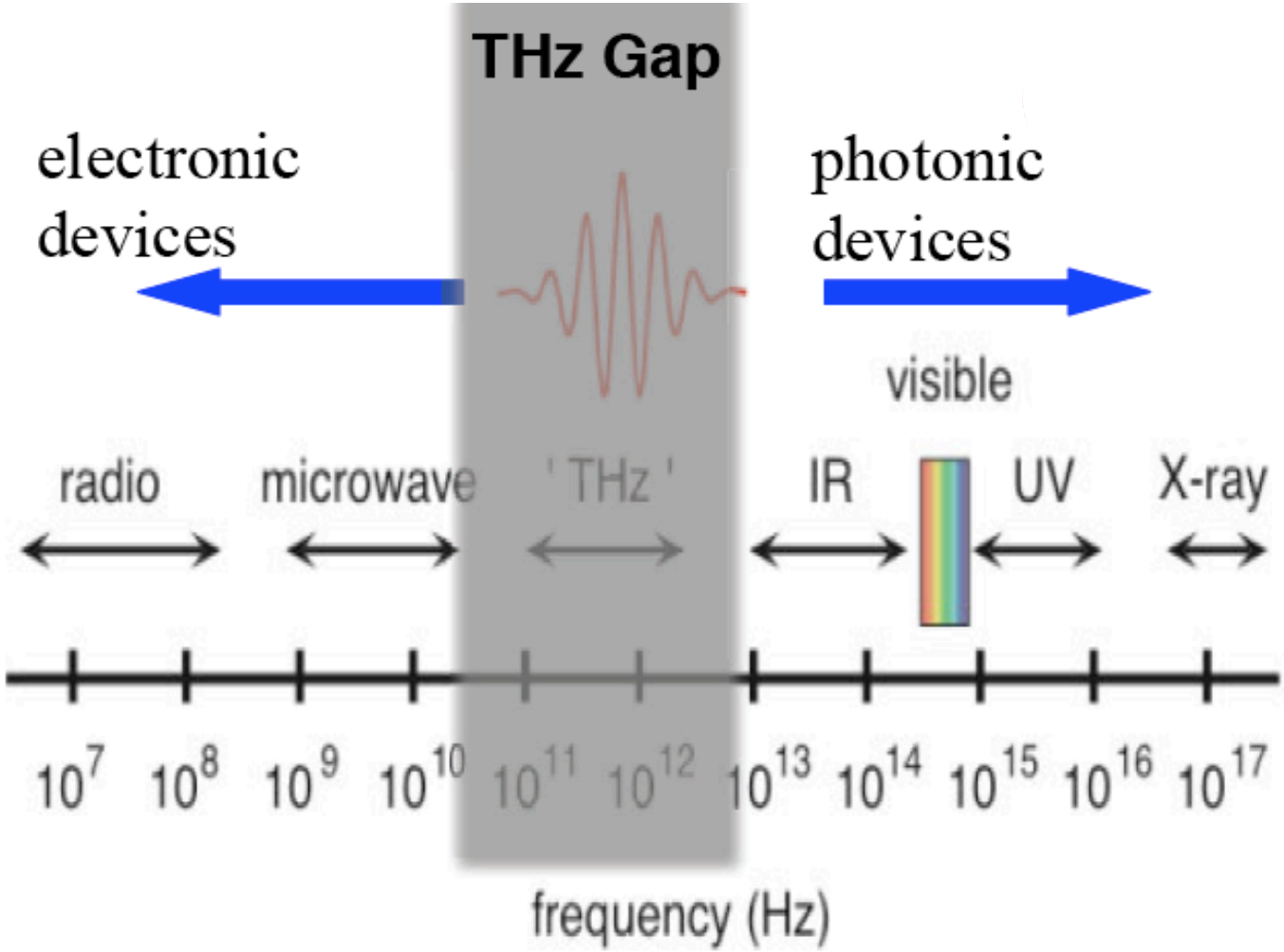
Workshop on Photonic Instruments

Thursday 24th of November 2011 Technopark - Zurich

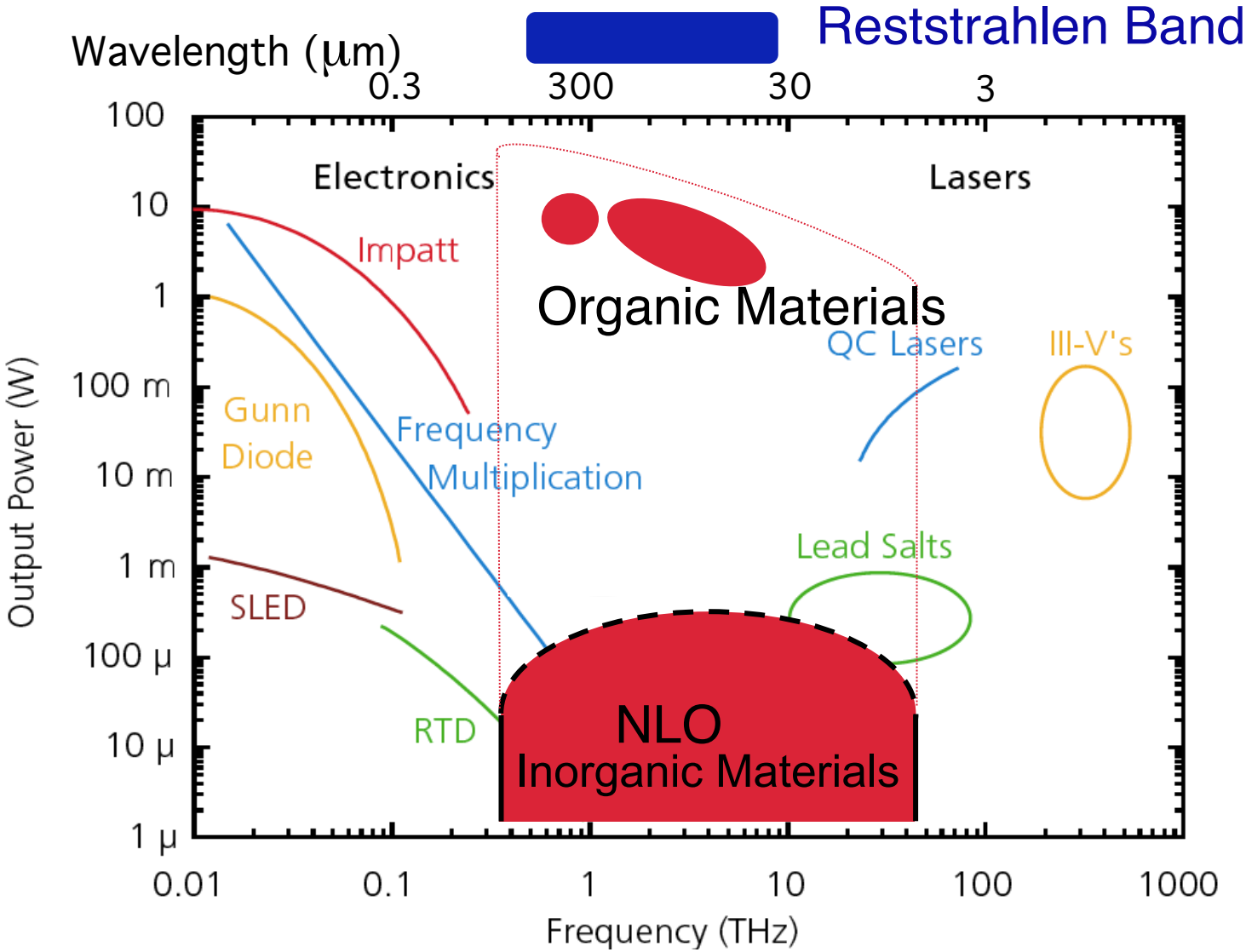
Terahertz Radiation



Terahertz Radiation

1. THz goes through clothing, and many different packing material like plastic and carton.
2. THz radiation is ideal for **materials testing**, security control and for inspection of packages.
3. THz radiation is ideal not ionizing, therefore not dangerous for people.
4. Explosives, biological agents, or pharmaceuticals show characteristic spectra in the THz regime.

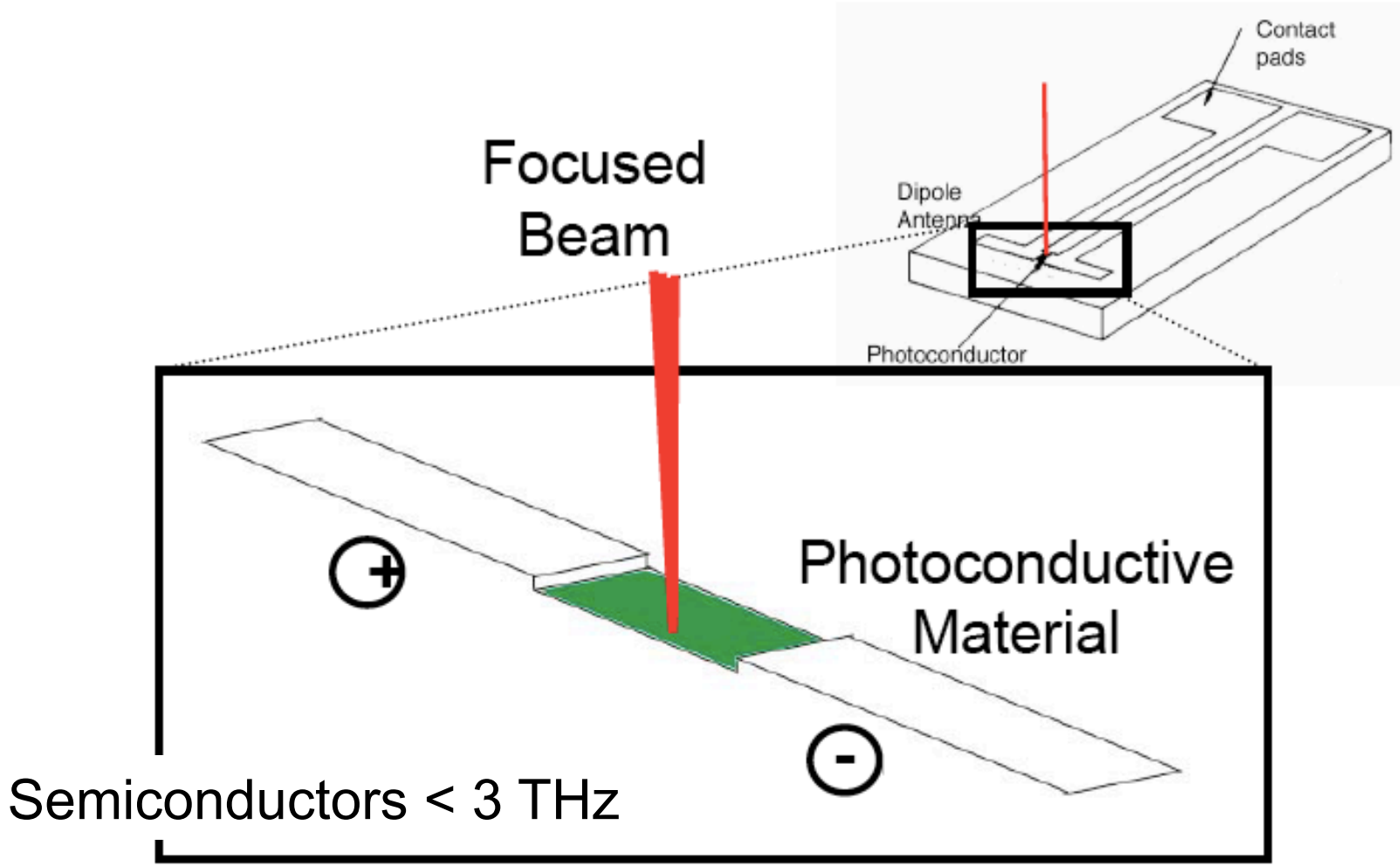
Electronics, THz Waves and Lasers



Terahertz Sources

- Auston Switch (Semiconductors < 3 THz)
- Quantum Cascade Lasers
- Optical Rectification up to 20 THz with organic materials
- Difference Frequency Generation 1 – 100 THz
- UTC-PD (< 1 THz)
- BackWOscillators

Auston Switch



The Quantum Cascade Laser

- Interband emission
- Specially designed band structure: quantum wells

- Low power
- Higher THz frequencies
- Cryogenic operation

Nonlinear Optical Techniques

difference-frequency generation

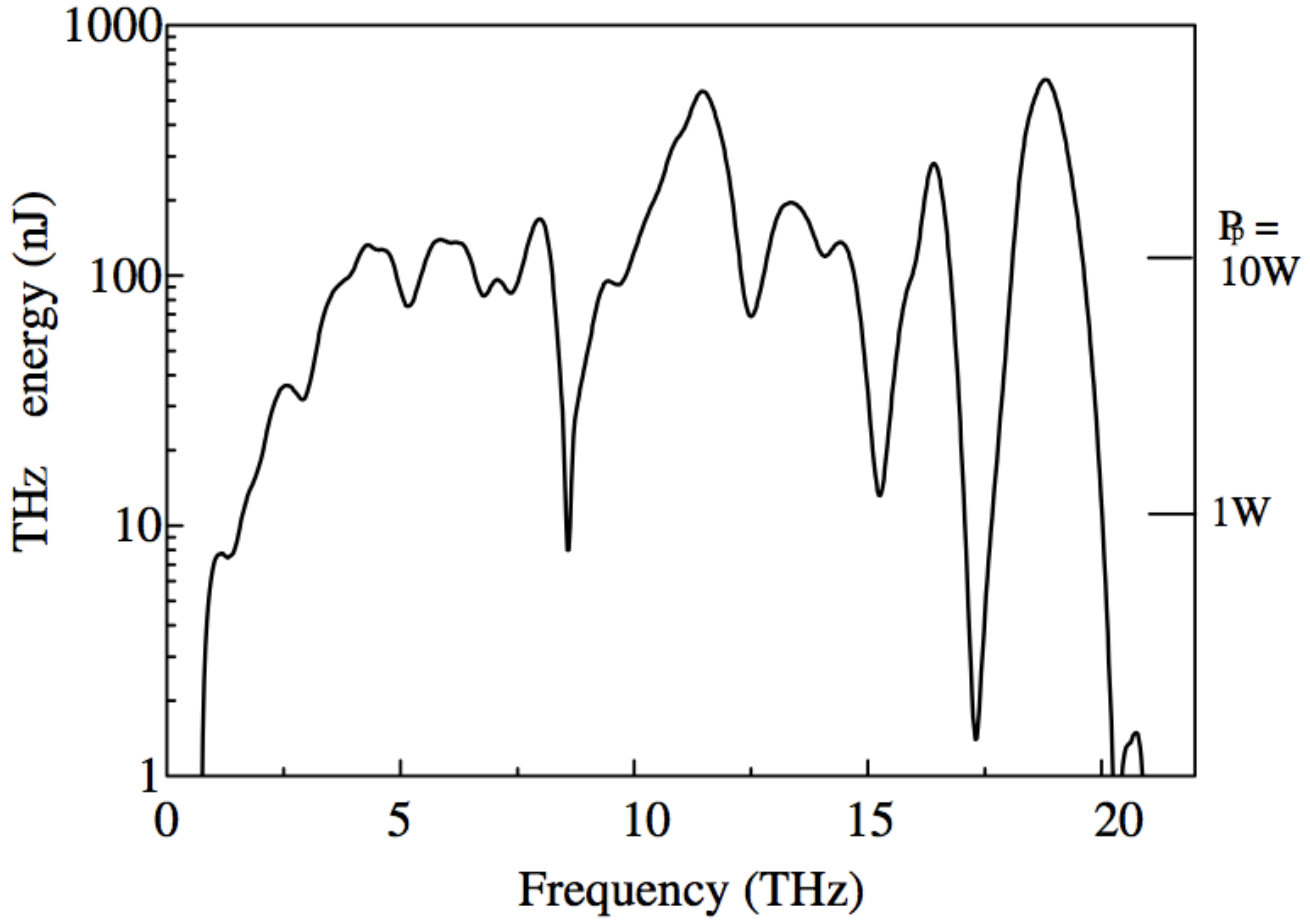
$$\omega_3 - \omega_1 \rightarrow \omega_2$$

special case: optical rectification

$$\omega - \omega \rightarrow \Omega \approx 0$$

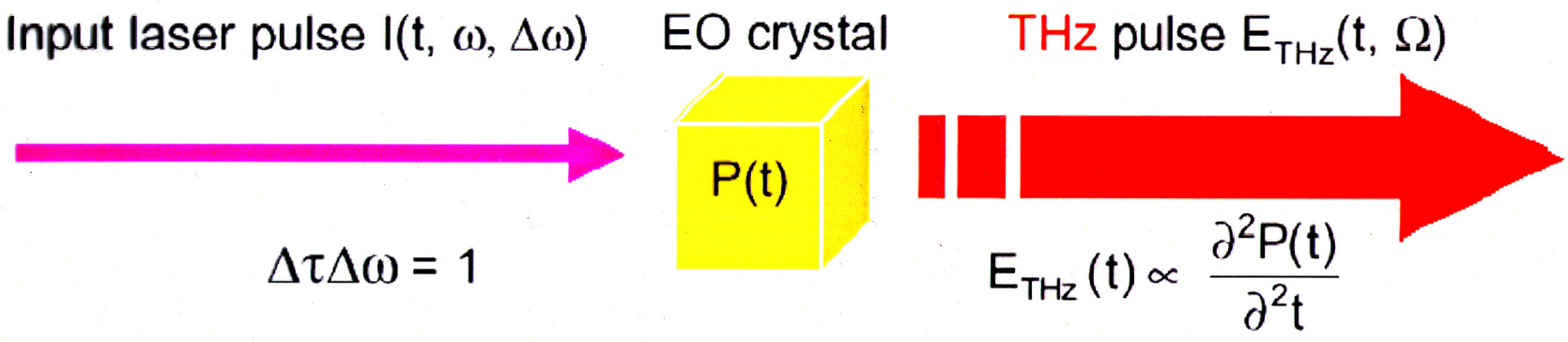
$$\left.\begin{aligned}\omega_1 &= \omega + \Omega/2 \\ \omega_2 &= \omega - \Omega/2\end{aligned}\right\} \Rightarrow \omega_1 - \omega_2 = \Omega \qquad (\ \omega \gg \Omega\ )$$

Energy of THz-Waves Generated in DAST



Reference: T. Taniuchi et al., *Nonlinear Optics, Quantum Optics*, 34, 57 (2005)

THz Optical Rectification



Beating frequency $\Omega < \Delta\omega$ (laser bandwidth)

Dielectric polarization: $P(\Omega) = \chi^{(2)}(\Omega, \omega+\Omega, -\omega)\, E(\omega+\Omega)E^*(\omega)$

$$E_{THz}(t) \propto \frac{\partial J(t)}{\partial t} = \frac{\partial^2 P(t)}{\partial^2 t} = \chi^{(2)} \frac{\partial^2 I(t)}{\partial^2 t}$$

NLO fs pulses

$$S(\omega) = S_0 \, \chi^{(2)} \, \omega^2 \, e^{-\tau^2\omega^2/2} \times \frac{1 - \exp\left(-\alpha(\omega) L_{crys}/2 - i \, \Delta k(\omega) L_{crys}\right)}{\alpha(\omega)/2 + i\Delta k(\omega)}$$

with $$\Delta k(\omega) = \frac{\omega \left(n(\omega) - n_{g,opt}\right)}{c}$$

Material independent: *Optical Rectification*

Material: *Nonlinearity*

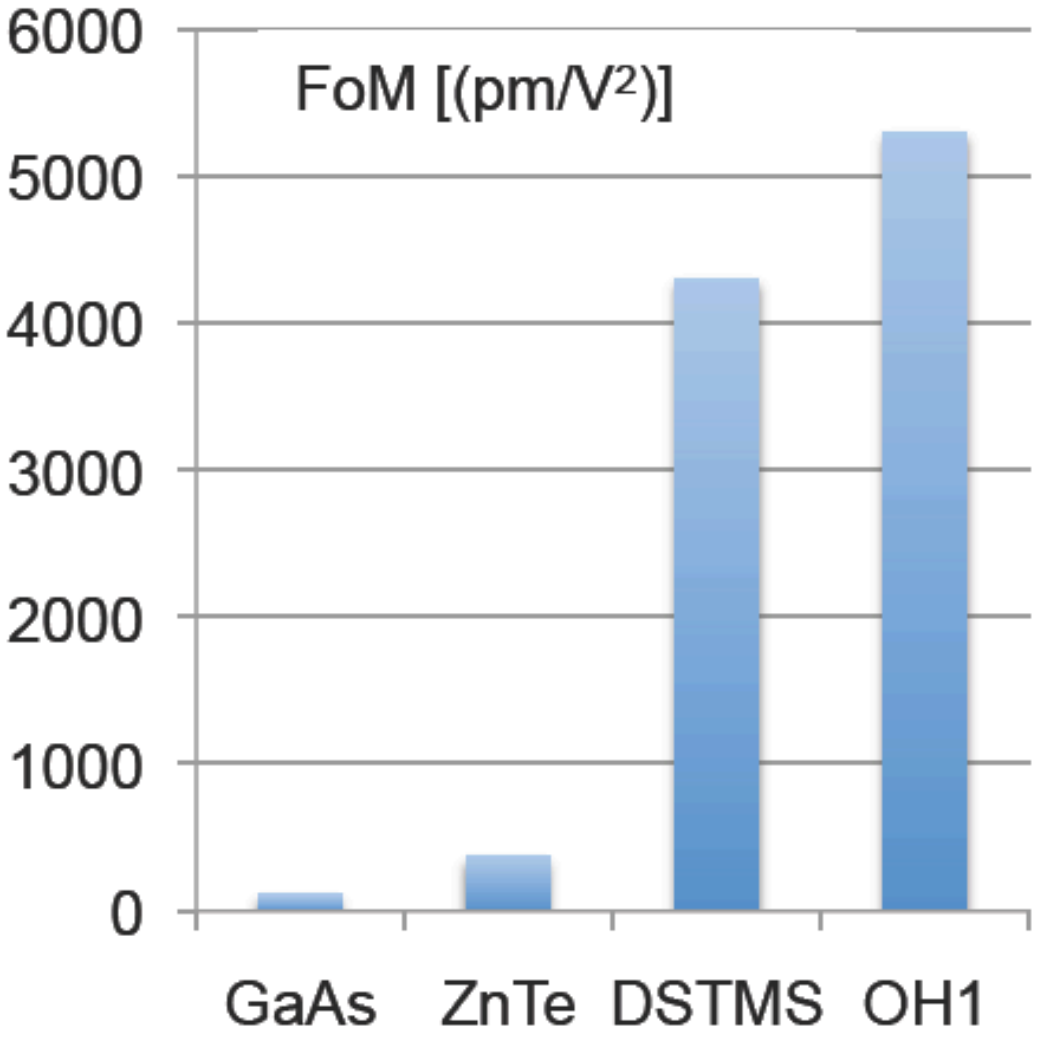
Material: *Propagation effects (Velocity-matching, absorption)*

Requirements for Efficient Generation

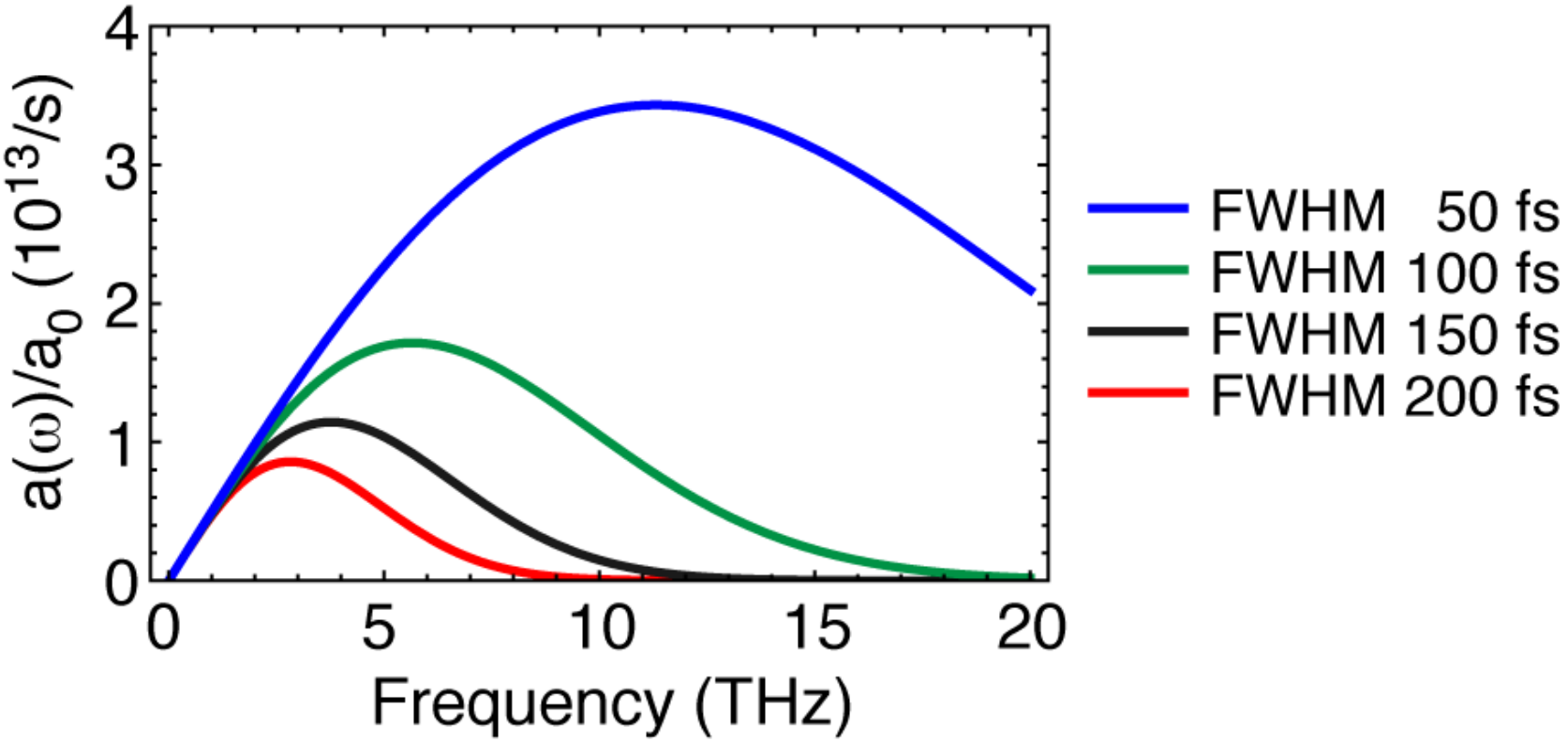
- Large nonlinear susceptibility: $\chi^{(2)}$
- Low absorption: α
- Velocity-matching between the optical and the THz pulse: $\Delta k=0$

Organic crystals satisfy all these conditions particularly well!

Figure of Merit



Source Term


a(ω)/a0 (10^13/s)
0
1
2
3
4
0
5
10
15
20
Frequency (THz)
FWHM 50 fs
FWHM 100 fs
FWHM 150 fs
FWHM 200 fs

Requirements for commercial sources

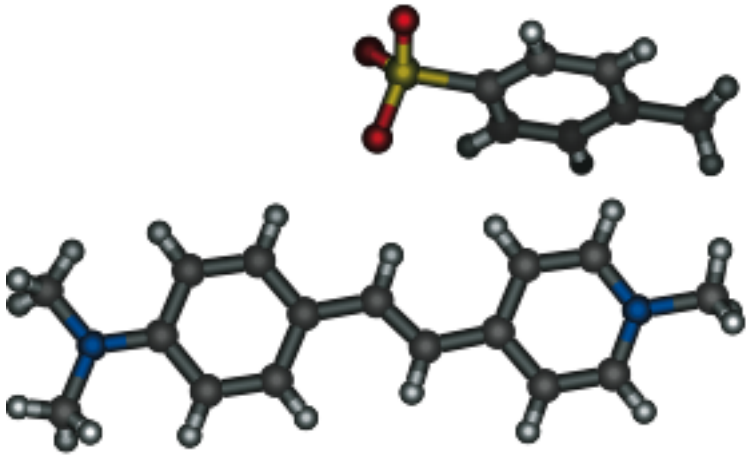
- Compact
- Turn-key operation
- Fast measuring time (high laser pump power, high nonlinear optical susceptibility)
- Reliable and maintenance free (all-solid-state)

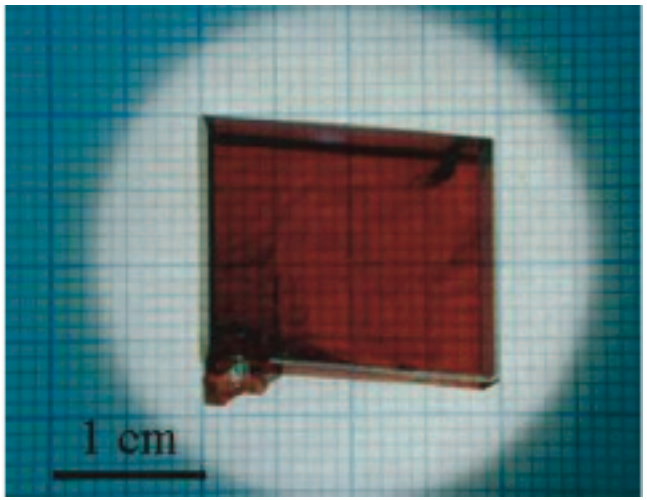
Our Solutions

- ***THz generators & detectors***
- ***TeraSys4000***
- ***TeraIMAGE***
- ***TeraTune (DFG and ns pulses)***

  Based on organic NLO materials and optical rectification

The Organic EO Crystal DAST





Highly birefringent (n_1-n_2 = 0.7 @ 800 nm)

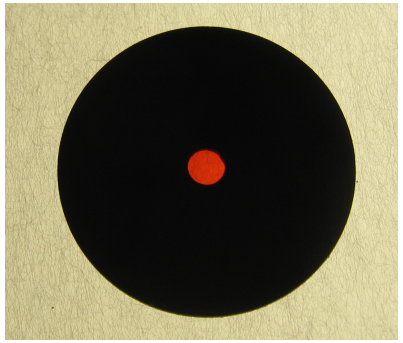
Electro-optic coefficient r_{11} = 77 pm/V

(ZnTe: 4 pm/V, GaAs: 1.5 pm/V)

(4-N,N-dimethylamino-4'-N'-methyl stilbazolium tosylate)

Producer: Rainbow Photonics AG

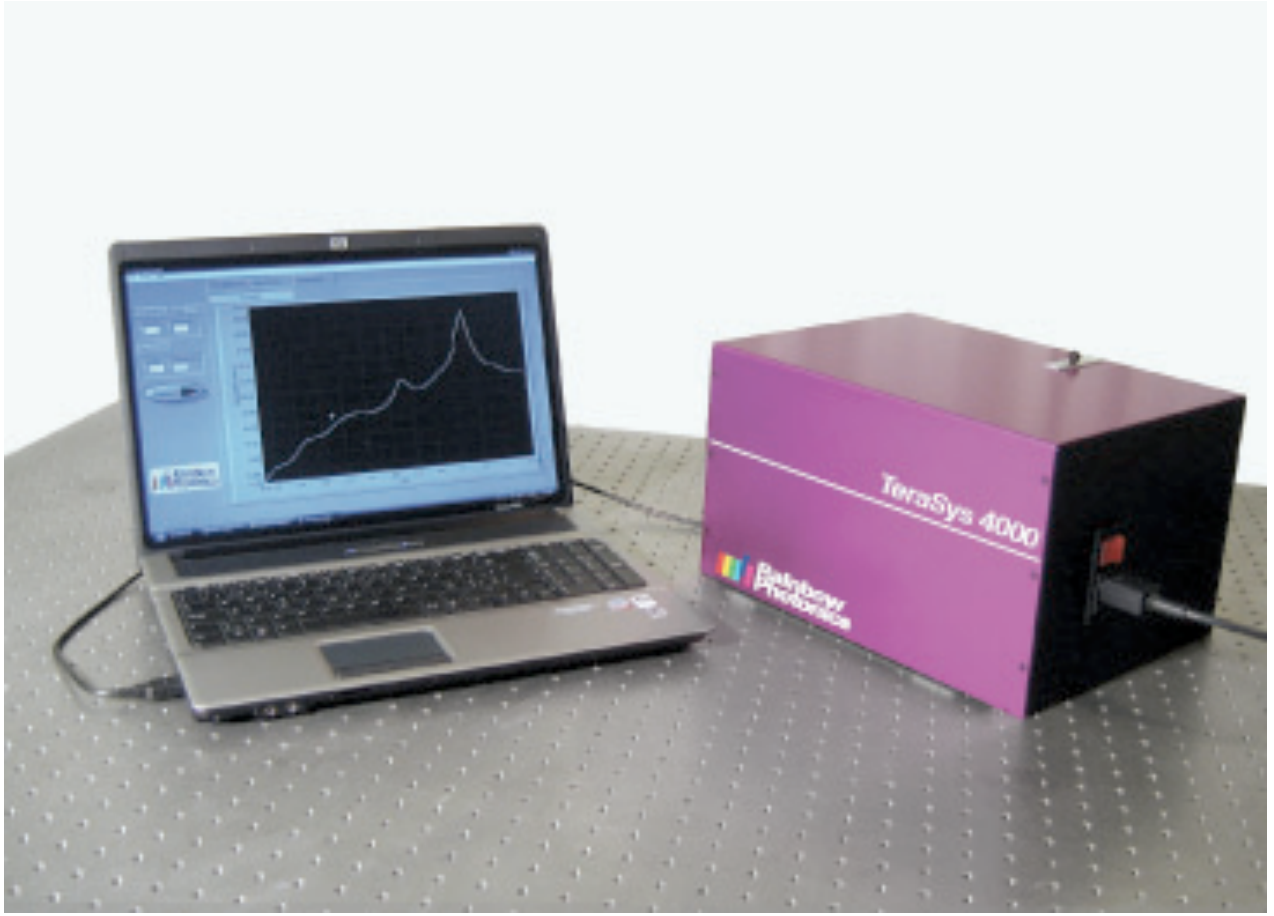
THz generators and detectors



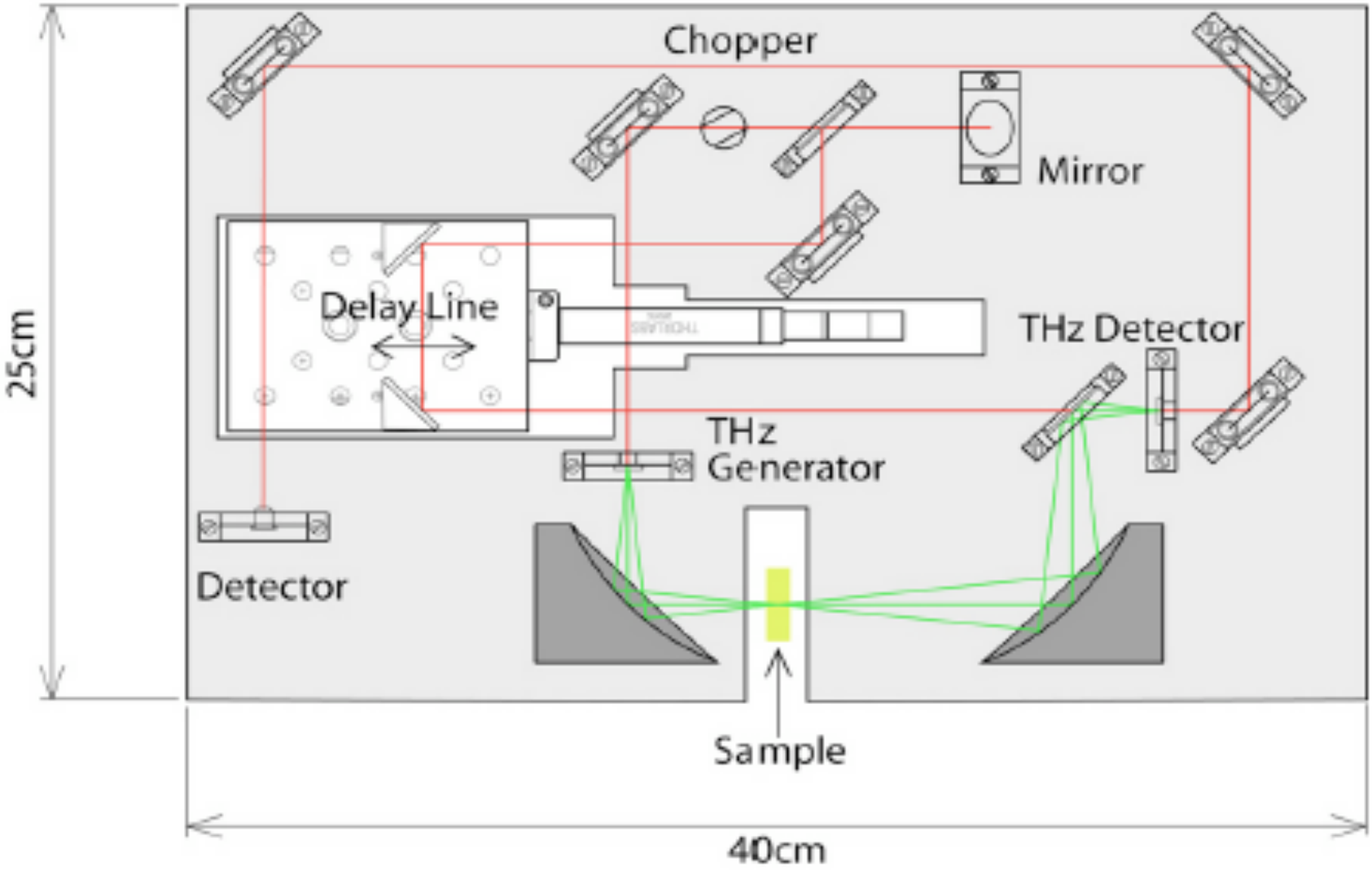
DAST/DSTMS/OH1

High damage threshold:
15 GW/cm^2 for fs @1.5 µm

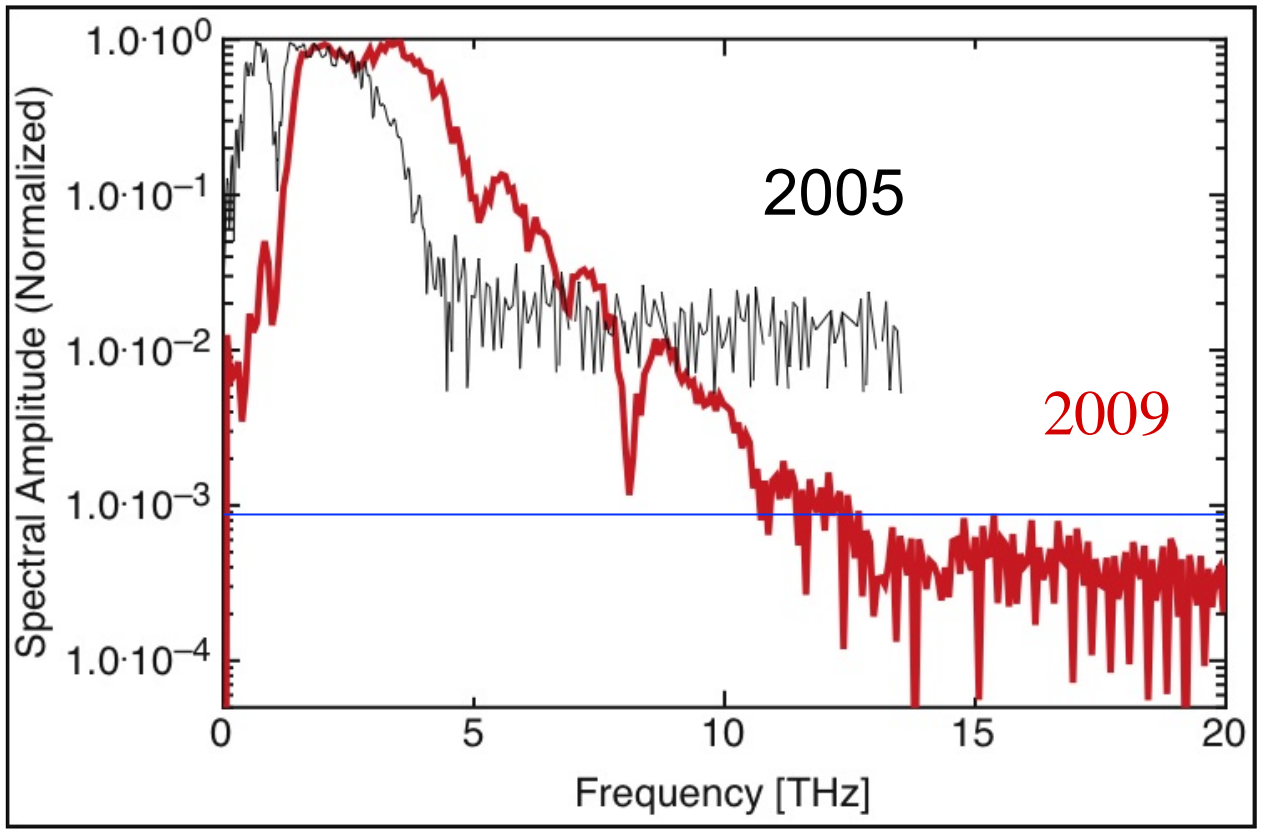
TeraSys 4000 (0.3 - 10 THz)



Rainbow Photonics Ltd


Chopper
Mirror
Delay Line
THz Detector
THz
Generator
Detector
25cm
Sample
40cm

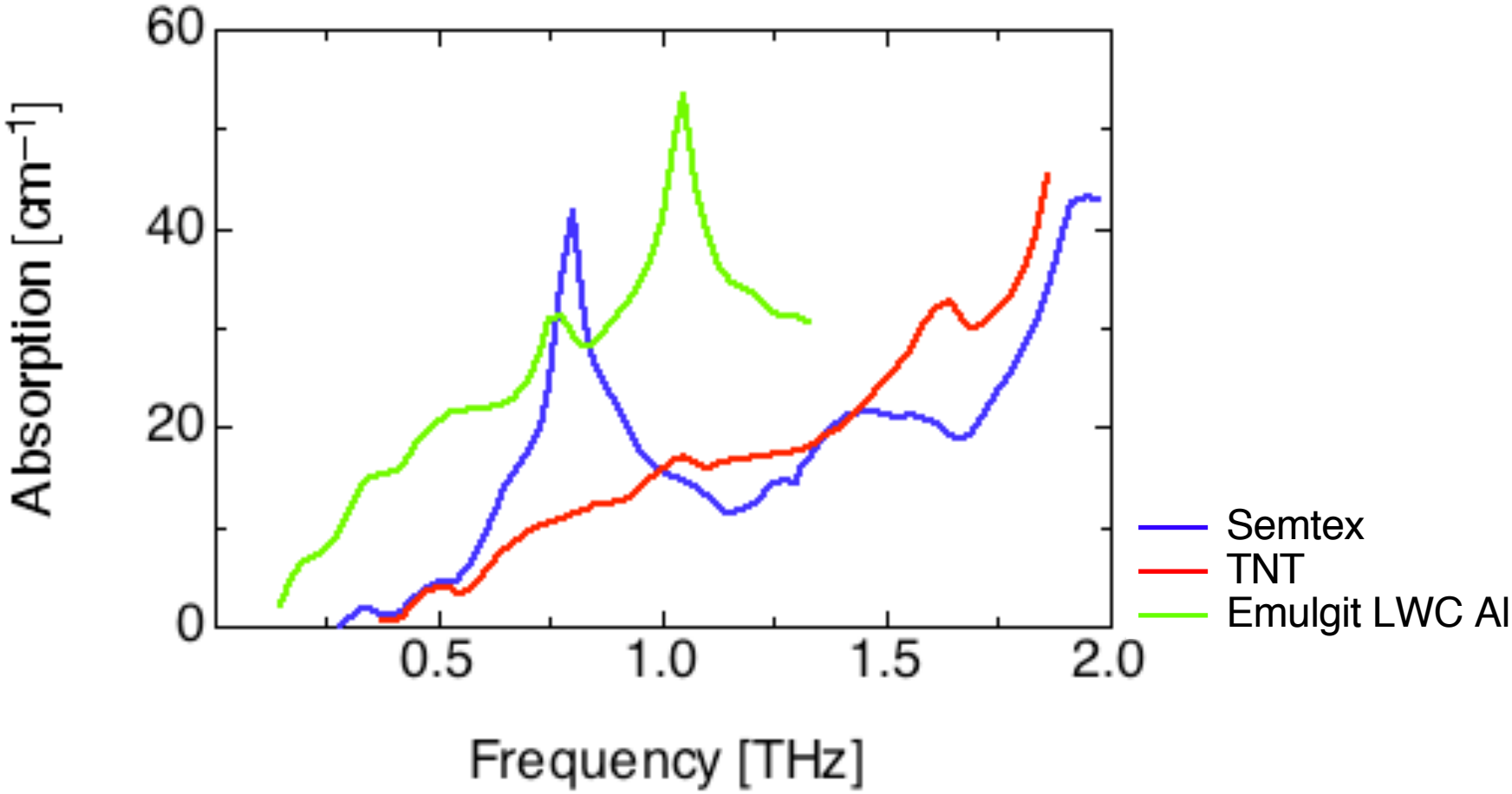
THz Generation in DSTMS



1.5 µm Laser:
- 70 fs
- 100 MHz
- P_{avg}=150 mW

- 0.3 to 12 THz
  (Small Resonances at 0.65/1.02/2.7/5.1/8.05 THz)
- Dynamic Range: 3 10^3 (65 dB Spectral Power)
- Scan Time: 20 s

THz Absorption of 3 Explosives

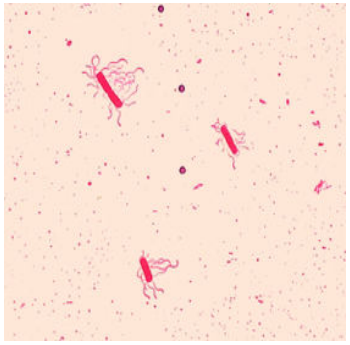


Rainbow Photonics AG

TeralMAGE

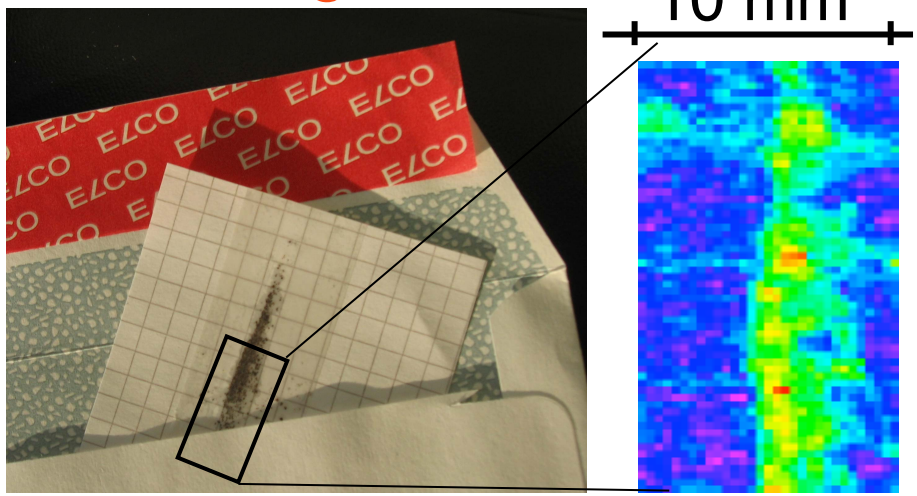
- Frequency range 0.3 – 16 THz
- Organic DAST, DSTMS and OH1 THz generators and detectors
- Scan area > 5x5 cm^2
- Computer controlled

THz imaging: Bacillus cereus spores



Bacillary, anaerobic and spore forming bacteria
→Food poisoning
→Closely related to B. anthracis!

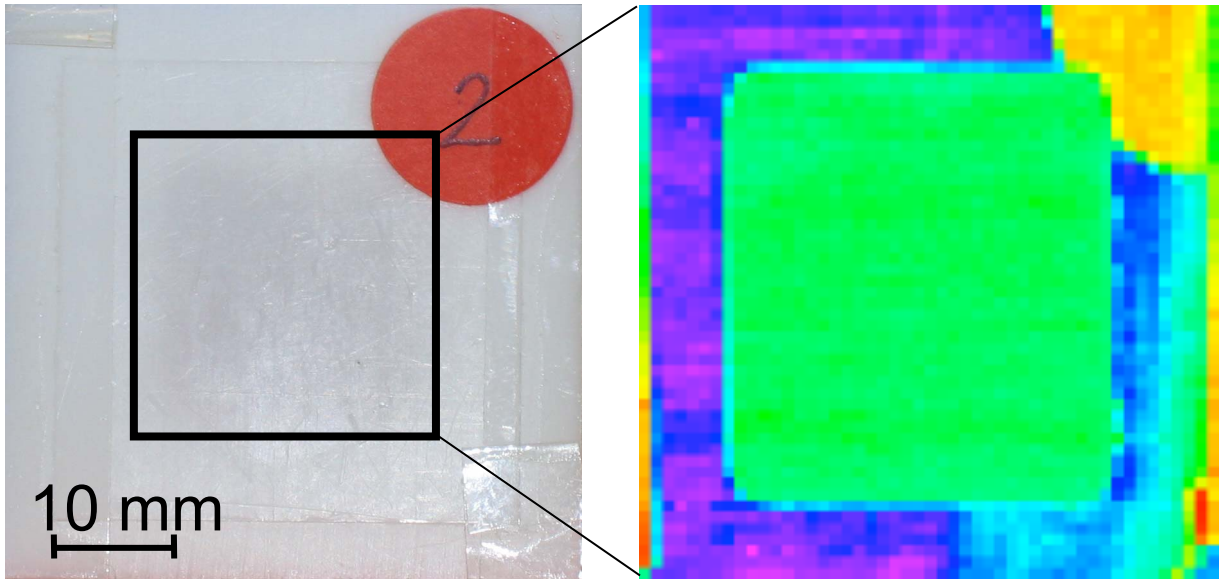
THz-Image



- Particle size ~1 micron
- ~ Monolayer
- Scanned area:
  7.5 x 15 mm
- 0.25 x 0.25 mm/pixel

THz-Image of Semtex

(a) (b)



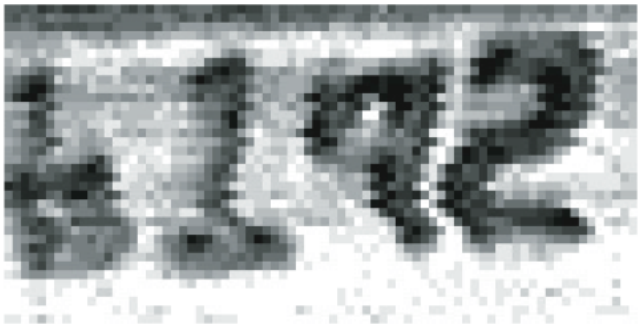
Semtex hidden in Teflon

Size: 25 x 25 mm

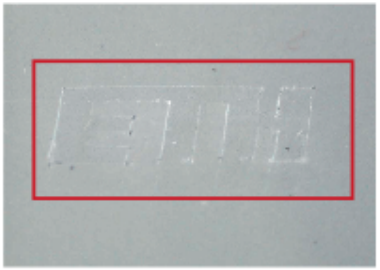
- No explosive
- Explosive
- Red paper sticker in upper right corner.

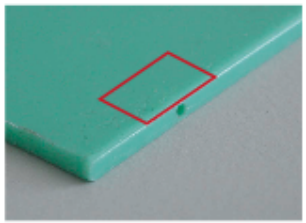
Application: THz Imaging

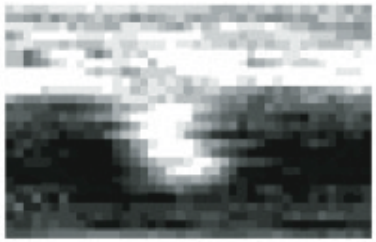
- Most dielectrics are transparent
- Conductors are opaque



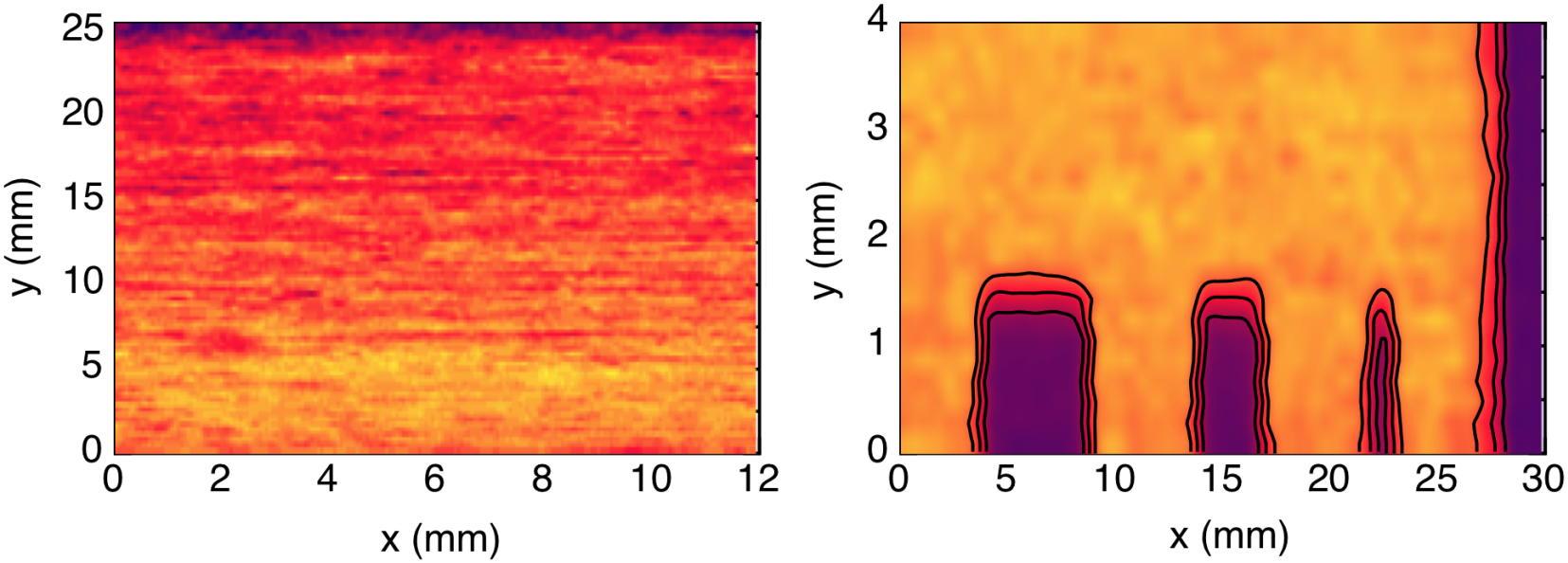
THz Images







Phase image (fixed time-delay)



Phase image acquired by terahertz pulse imaging.

Left panel: UHMWPE plate without any defects.

Right panel: UHMWPE plate with defects.

THz Wave Technology Offers

- Coherent Radiation with Amplitude and Phase Information
- High Spectral Resolution
  (up to 0.005 THz (0.17 cm^{-1})
- Wide Spectrum for Spectral Fingerprint Selectivity (particularly with DSTMS)
- 2 (and 3)- Dimensional Images
- Spatial Resolution of Less Than 0.1 mm

Outlook: Future Systems Requirements

- Femtosecond pump fiber lasers – **OR**
  - Average power > 2W
  - Pulse length: 10 – 80 fs
  - Rep. rate: 10 – 100 MHz
- Nanosecond pump lasers – **DFG**
  - Average power > 200 mW
  - Pulse length: 0.5 – 5 ns
  - Rep. rate: 0.1 – 10 kHz

Rainbow Photonics AG

Key Personnel

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ETH Spin-off of the Nonlinear Optics Laboratory ETHZ (1997)

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