THz Radiation: Opportunity with ERL Prototype

Contents:

- What are T-rays?
- How to make them?
- Spectroscopic techniques for THz range
- Applications
- ERL prototype as a source of T-rays

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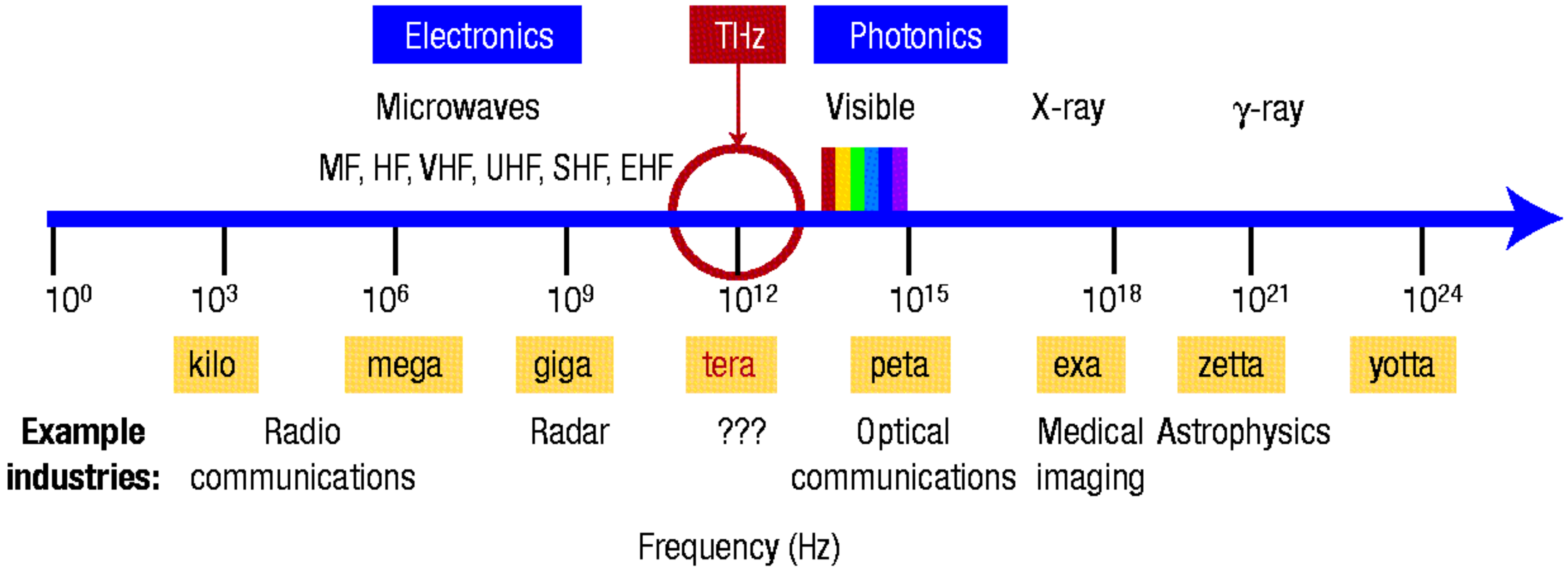
What are T-rays?



THz range is roughly defined as frequency	0.1 – 10 THz
wavelength	0.03 – 3 mm
energy	0.4 – 40 meV

e.g. 300 °K = 25 meV

Recent review paper:
Ferguson and Zhang in Nature 2002
“Materials for THz science and technology”

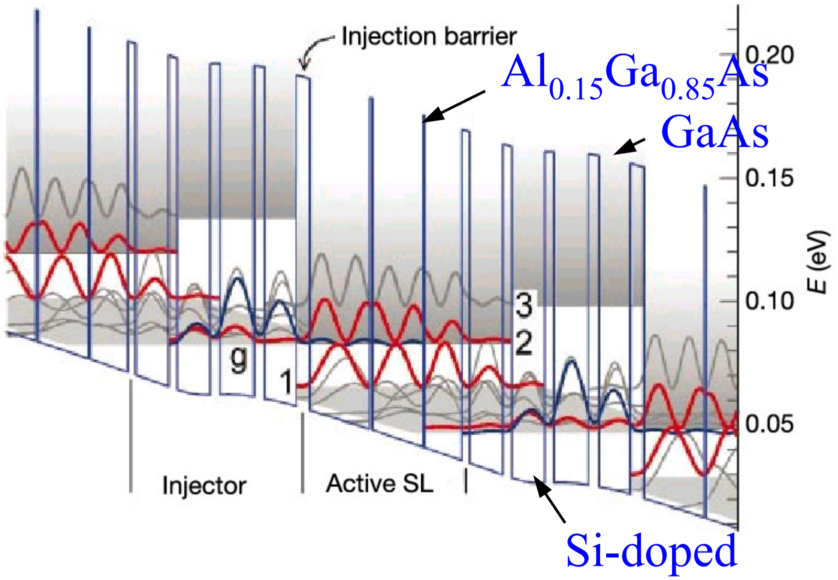
How to make them?

- Incoherent thermal sources
- Broad-band pulsed sources
  - Photoswitches
  - Optical rectification
  - Accelerators
- Narrowband CW sources
  - Molecular lasers
  - RF upconversion, optical downconversion
  - Semiconductor cascade lasers New!

Narrowband CW sources

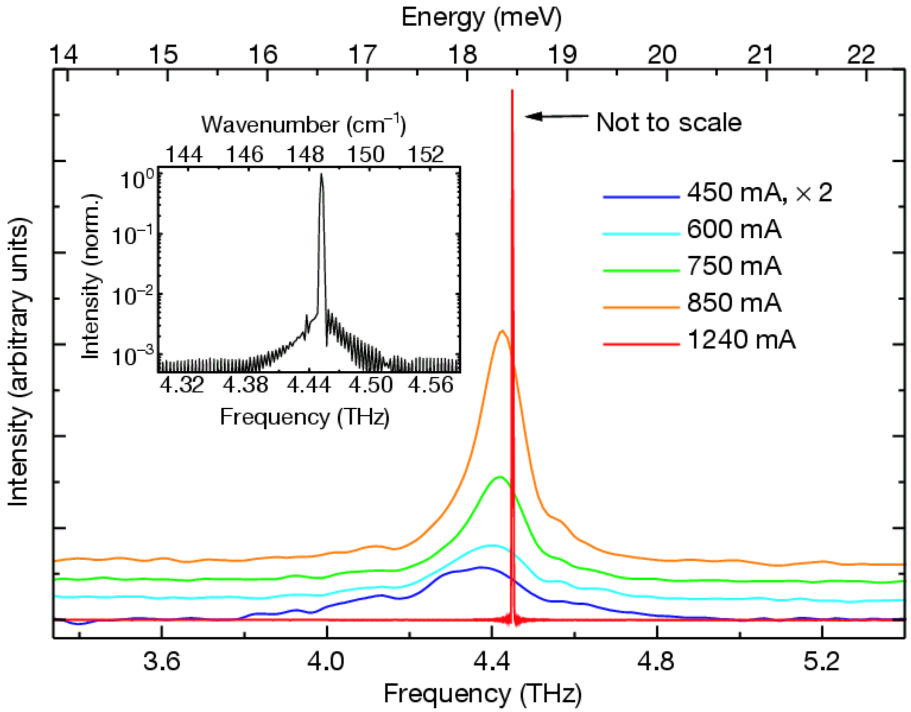
- E.g. important for potential applications in telecommunications for high-bandwidth intersatellite links
- Upconversion of microwaves
  - low efficiency (< 100 μW)
  - highest frequency 2.7 THz
- Molecular Laser
  - low-pressure gas cavity pumped by CO_2 laser
  - THz output < 30 mW
  - bulky (kW power)
- Photomixing of two lasers
  - broadly tunable
  - max power 100 mW

Quantum Cascade Laser



Kohler, et al. in Nature 2002
"THz semiconductor heterostructure laser"

At 8 K, 1 A current, laser device (1.24-mm by 180-µm) produced above 2 mW at 4.4 THz



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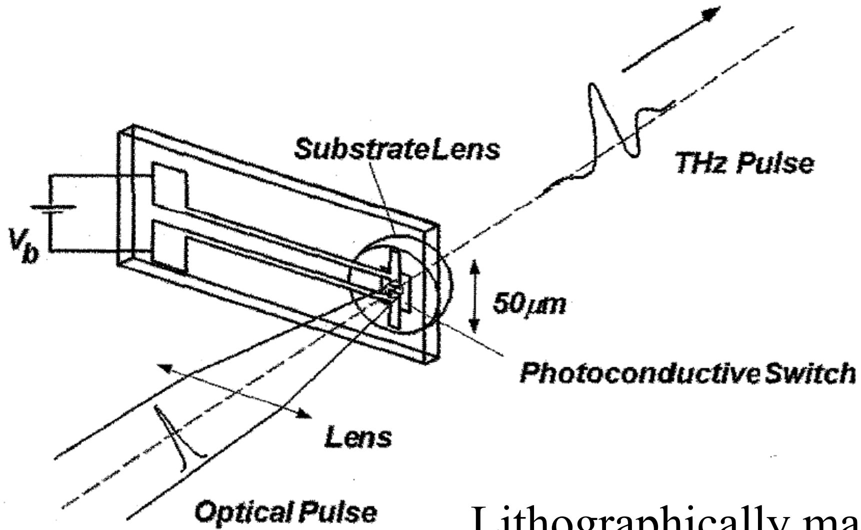
Pulsed Broadband THz Source – Photoswitches

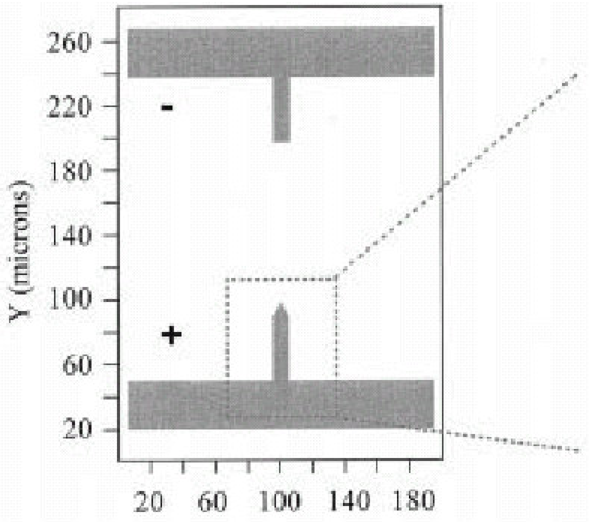


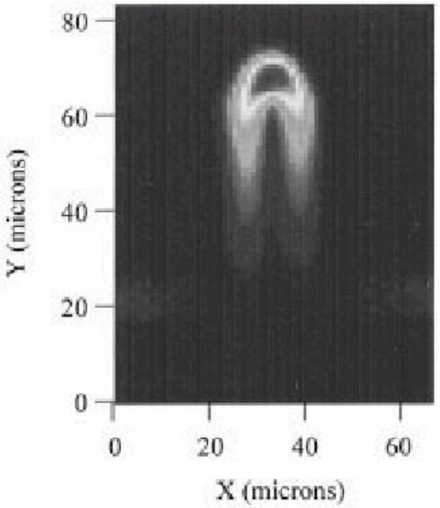
Nuss in IEEE Circuits and Devices 1996
"Chemistry is right for T-ray imaging"

Average THz power: > 40 μW

Bandwidth: 4 THz

Lithographically manufactured switch





Mittleman et al. in IEEE Quantum Elect. 1996
"T-ray imaging"

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Photoswitches

- Undoped LT-GaAs, InP, and rd-SOS as a substrate
- Photocurrent rise time ~ 0.2 ps, pulse duration ~ 0.5 ps
- So far people have used Ar laser pumped Ti:Sapphire (6 gal/min for pump cooling, 60 amp 480 V three-phase power supply)
- Cr:LiSAF diode-pumped laser available now is a much better choice
- THz setup price $50K → $10K

Optical Rectification

- A fs laser is needed
- THz energy comes from the pulse itself
- Uses inverse electro-optic effect
- Lower power than photoswitches but spectrum extends to 50 THz

Accelerators: Relativistic Electrons

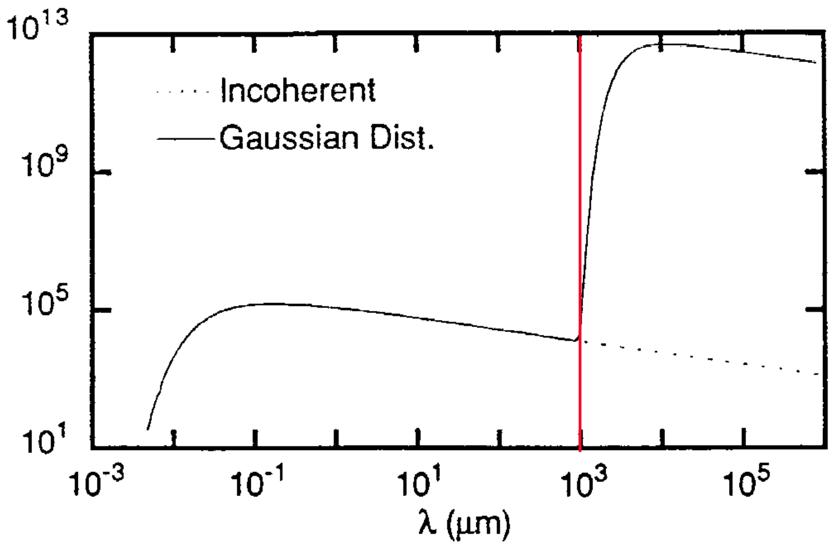
- A short bunch radiates as a super electron of charge *Ne* at wavelength >> bunch length
- Works for various ways of light production as long as spectrum from a single electron covers ~ bunch length wavelength part:
  - bending magnet
  - diffraction radiation
  - transition radiation
  - (dedicated) undulator (can be FEL)
- Much higher powers are available (hundreds of W for an ERL)

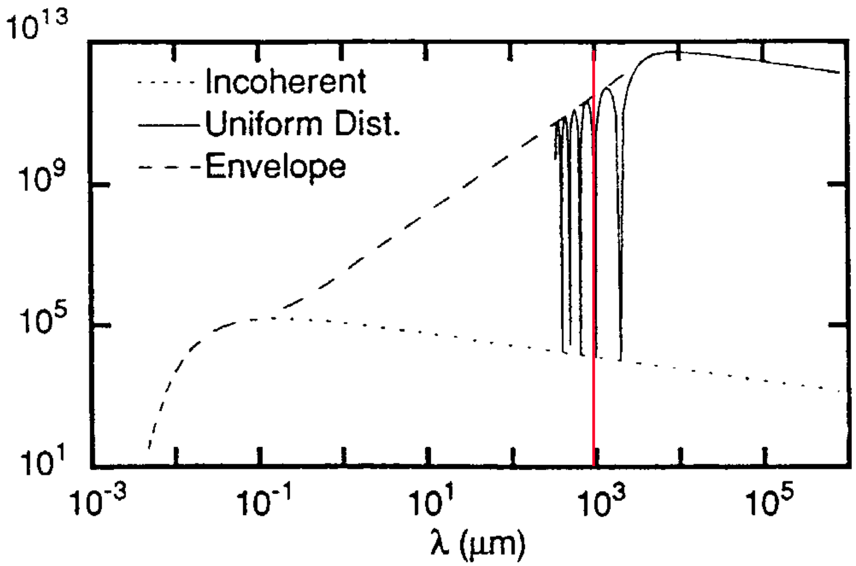
Incursion into Jackson

single electron: $$\frac{d^2 I_0}{d\omega d\Omega} = \frac{e^2\omega^2}{4\pi^2 c}\left|\int_{-\infty}^{\infty} \mathbf{n}\times(\mathbf{n}\times\boldsymbol{\beta})\, e^{i\omega[t-\mathbf{n}\cdot\mathbf{r}(t)/c]}\,dt\right|^2$$

electron bunch: $$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2\omega^2}{4\pi^2 c}\left|\int_{-\infty}^{\infty} \sum_{i=1}^{N} \mathbf{n}\times(\mathbf{n}\times\boldsymbol{\beta}_i)\, e^{i\omega[t-\mathbf{n}\cdot\mathbf{r}_i(t)/c]}\,dt\right|^2$$

$$\frac{d^2 I}{d\omega d\Omega} = [N + N(N-1)f(\omega)]\frac{d^2 I_0}{d\omega d\Omega},\quad f(\omega) = \left|\int \exp\left(\frac{i\omega z}{c}\right) S(z)\,dz\right|^2,\ \text{for } N \to \infty$$





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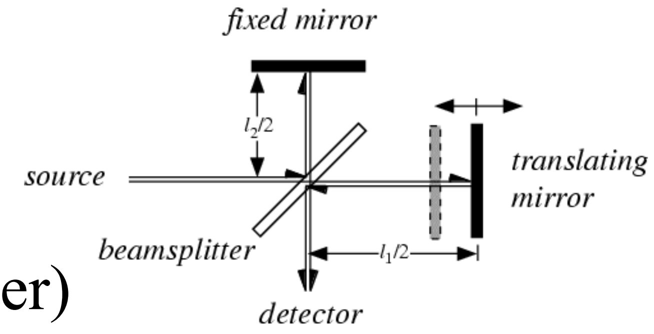
Coherent Radiation from a Bending Magnet

- Energy independent (as long as critical SR wavelength λ_c << bunch length,
  here λ_c [mm] = 0.559 ρ[m] / E^3 [MeV])
- One needs the right bunch length (depending on longitudinal distribution: ~ 10 – 0.1 ps FWHM)
- What about a bunch with large aspect ratio (short, but wide)?

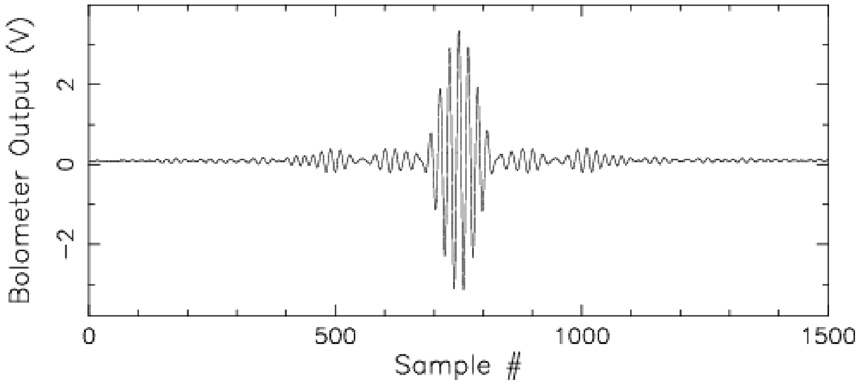
Spectroscopic techniques for THz range

- Fourier Transform Spectroscopy (FTS)
- Narrowband Spectroscopy
- THz Time Domain Spectroscopy (THz TDS)
- Detecting THz radiation

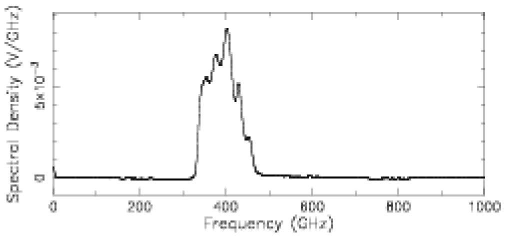
Fourier Transform Spectroscopy



- Well established
- Uses broadband (thermal) source +
- Direct detection (LHe cooled bolometer)
- Pros: wide spectral range (THz to infrared)
- Cons: limited spectral resolution, $(\Delta\lambda/\lambda)^{-1} = 2\,L_{\mathrm{mirror}}/\,\lambda$



$\xrightarrow{FT}$



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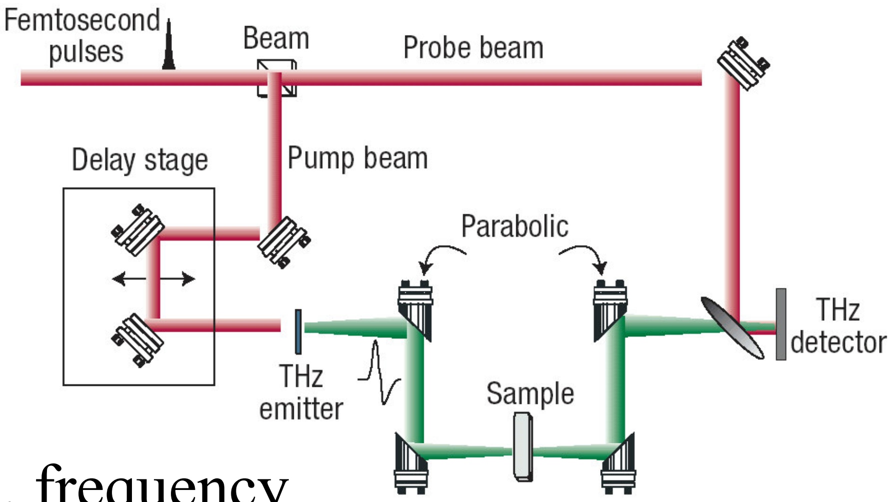
THz Time Domain Spectroscopy (THz-TDS)



- Relatively new technique
- Uses short THz pulses
- Coherent detection:
  - measure field $E(t)$
  - FT → amplitude, phase vs. frequency
- Cons: coarser than narrowband spectroscopy, smaller range than FTS
- Pros: high sensitivity & time-resolved phase information. Can be combined with imaging, e.g. spectroscopic images of the sample.

Example: 2 – 5 THz bw, 50 GHz resolution, acquisition time < 1 min, E-field range 10^5

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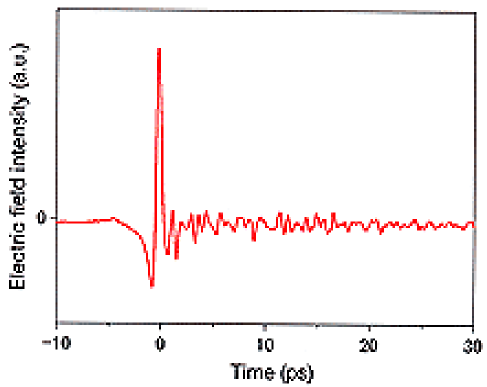
THz-TDS

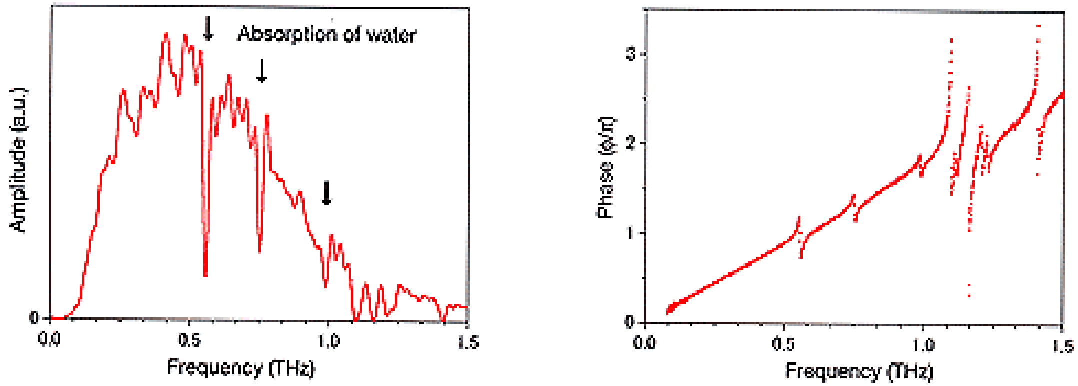
http://www.tochigi-nikon.co.jp/technologies/terahertz/eng/index.html



1THz

Wave number: 33.3cm^{-1}

Wavelength: 0.3mm



water vapor THz-TDS spectrum

Spectral range:4cm^{-1} to 60cm^{-1}

(0.12THz to 1.8THz)

Rexolution:≦4cm^{-1}

(≦0.12THz)

THz Pulse Spectroscopy System
(RAYFACT-TDS-001R)

THz Detectors

- THz-TDS can use identical antenna to that of the optical switch. Broadband (up to 30 – 60 THz)
- Electro-optical sampling. Allows spectrum collection over a single shot.
- Note: no fast electronics is needed.
- Broadband detection Si, Ge and InSb bolometers (LHe cooled)
- High spectral resolution heterodyne sensors. LO is also ~ THz. Downshifted and amplified signal is measured.

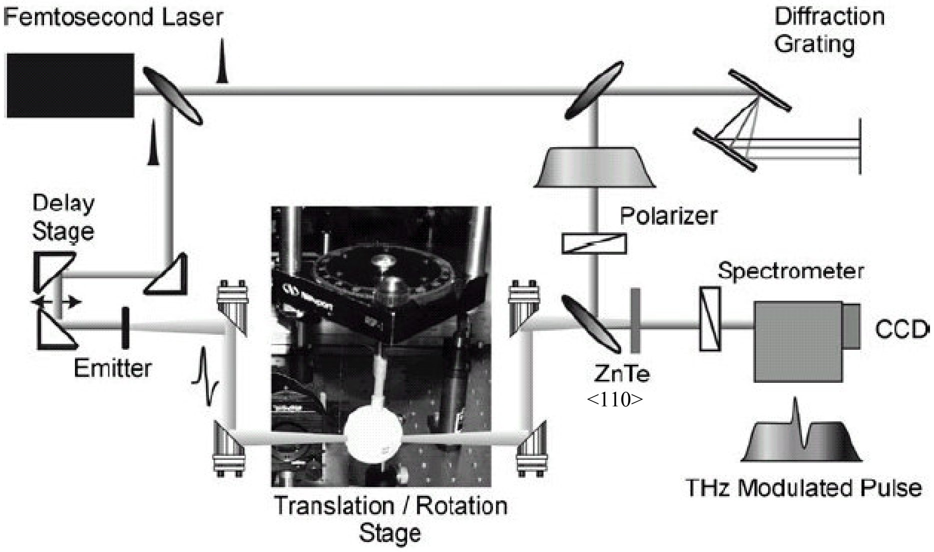
Applications

- Imaging
- Chemical analysis
- Communication
- Biomedical applications
- THz Hall effect
- Study of high-T_c superconductors

Imaging

- Throughput is an issue
- Electro-optic THz detection is generally preferred
- Resolution is limited by the wavelength to sub-mm
- Other techniques are used
    - dark-field imaging
    - near-field imaging (7 µm best resolution)
- Wealth of information is available; advanced processing techniques can be used to extract specific information

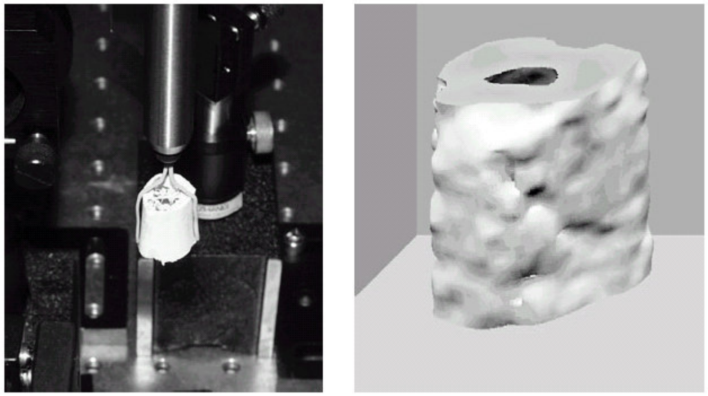
THz Imaging using electro-optic detection



Ferguson, et al. in Phys. Med. Biol. 2002
"Towards functional 3D T-ray imaging"

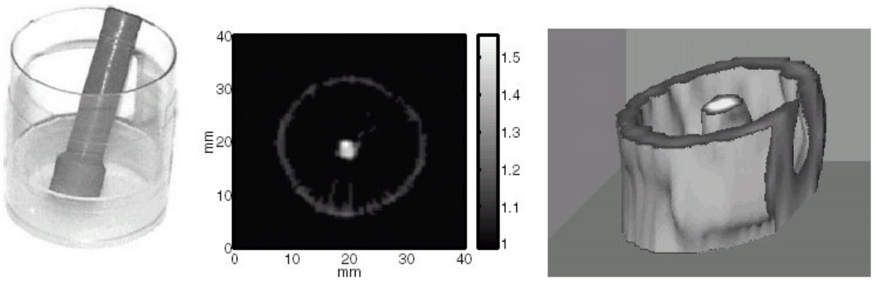
Cons: poorer SNR 100:1 as opposed 10000:1 for 'traditional' THz-TDS
Pros: speed

T-ray tomography examples
acquisition time ~ several hours
$n(\omega)$ info in 3D



(a) (b)

turkey bone



(a) (b) (c)

vial and plastic tube

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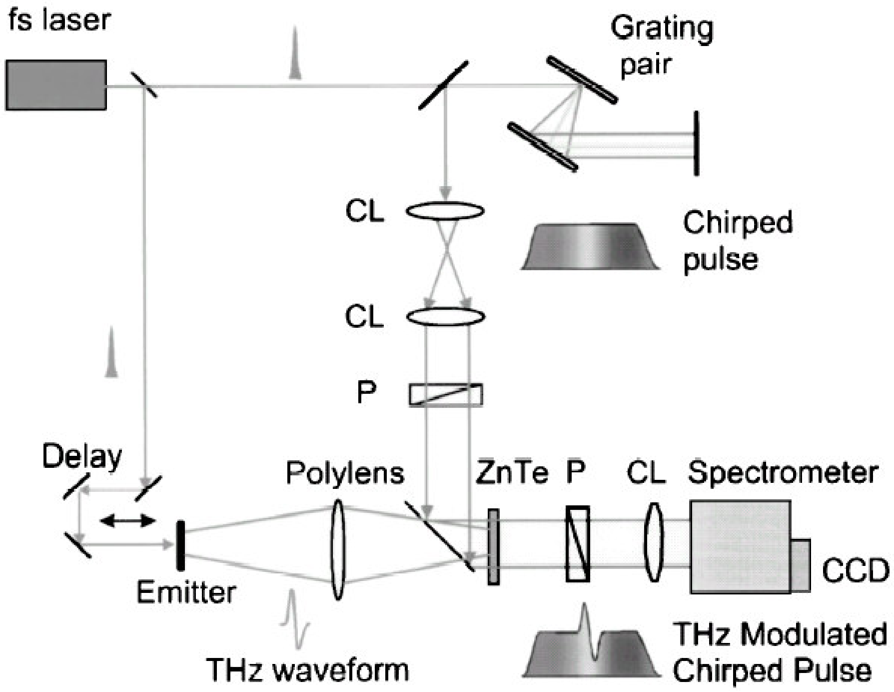
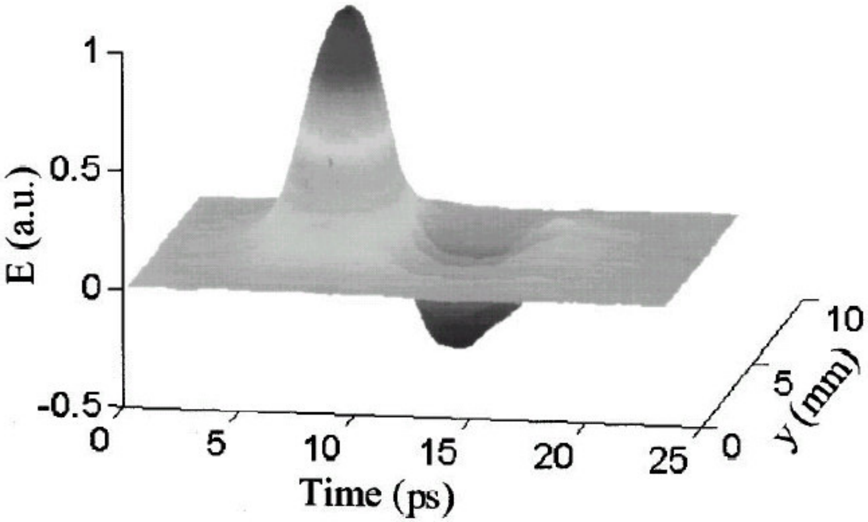
Spatiotemporal imaging



Jiang and Zhang in Opt. Let. 1998 “Single-shot spatiotemporal THz field imaging”

dipole radiator 1D spatiotemporal image →
(available at video rate)



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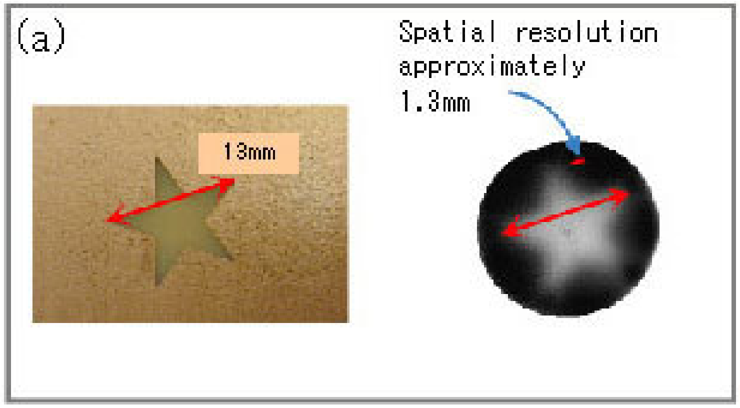
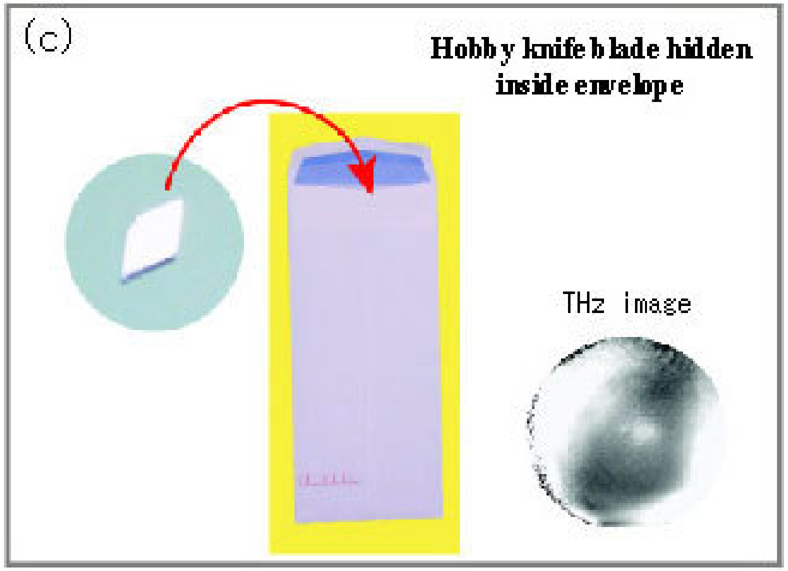
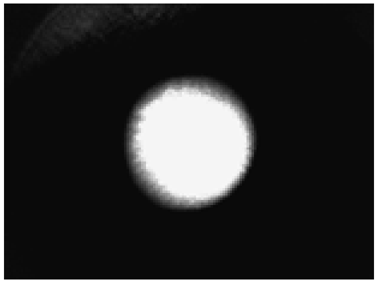
Examples

http://www.tochigi-nikon.co.jp/technologies/terahertz/eng/index.html

Real-time Imaging System (RAYFACT-RIM-001EX)







THz light waveform at 0.3 ps

$$$ Images $$$

$$$ Images $$$

$$$ Images $$$

Can you see a gun?

$$$ Images $$$

What about knife?

Can you see a gun?

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Chemical Analysis

- Rotational, skeletal vibrations
- Many large molecules have unique spectrum in this range (fingerprint region)
- Flame spectroscopy
- Gas sensor (auto). Not sensitive to the presence of particulates (soot)
- Likely to use heterodyne detection to improve frequency resolution
- Good for detection of simple molecules (H_2O, CO, O_2, etc. – traditional application in astronomy and space)

THz Communication

Thz Sources and Systems, ed. by Miles, Harrison and Lippens, NATO Science Series

- There is a window in H_2O absorption around 400 GHz
- Transmission range is comparable with 60 GHz radiation due to increased gain of antenna ($\propto \lambda^2$) of the same area
- Has to be relatively short distance (point-to-point)

  E.g. for 6 dBm (4 mW) source and receiver's sensitivity of -90 dBm, transmission length is 2.0 km. Increasing trans. power by 10^3 increases the range by only 1 km!
- More resistant to fog, smoke than IR
- Channel capacity is estimated to be 380 Gbps (for comparison ISDN is 600 Mbps)
- Challenges in THz circuitry manufacturing (state of the art ~ 100 GHz)

Biomedical applications

Fitzgerald et al. in Phys. Med. Biol. 2002, "An introduction to medical imaging with coherent THz frequency radiation"

Pros:

- Non-ionizing
- Far less Rayleigh scattering ($\propto \lambda^{-4}$)

Cons:

- Water (although could be an advantage, e.g. monitoring water-content in burns). THz penetration length is ~ 1 mm
- Resolution limited in con-focal microscopy to $\lambda/\sqrt{2}$

complex refr. index

$$t = \frac{E_t(\nu)}{E_0(\nu)} \approx t_{01}(\nu) t_{02}(\nu) e^{i\hat{n}(\nu)kd}$$

transmission

Fresnel coefficients

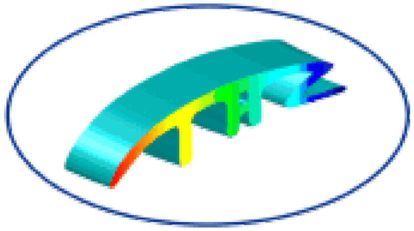
Biomedical Applications: Exposure Limits

- Specified in terms of maximum permissible exposure (MPE)

$$\mathrm{MPE}_{\mathrm{PW}} = \frac{\mathrm{A} \times \mathrm{MPE}_{\mathrm{CW}}}{F \times t}, \quad \mathrm{MPE}_{\mathrm{CW}} = 100 \frac{\mathrm{mW}}{\mathrm{cm}^2}$$

- Sources now typically have ~ 1 μW at best
- Generally speaking 1 mW CW is at the threshold for medical applications
- THz-bridge project

http://www.frascati.enea.it/THz-BRIDGE/



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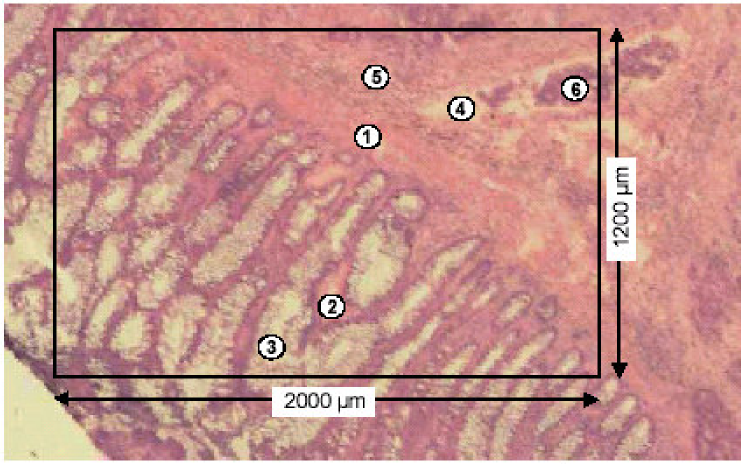
Biomedical Application Example

Lasch et al., “Imaging of human colon carcinoma thin sections by FTR-IR microspectrometry”



1: L. muscularis mucosae

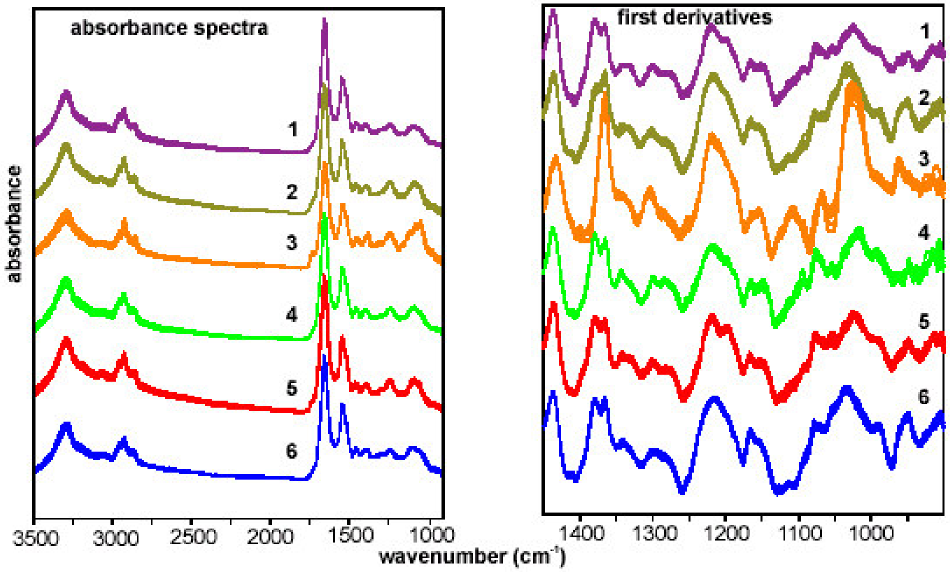
2: L. propria mucosae

3: crypts

4: unknown structure

5: connective tissue

6: adenocarcinoma



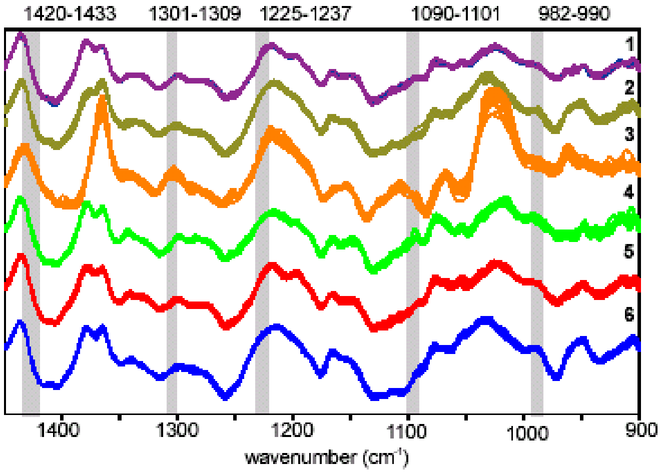
Basic idea:

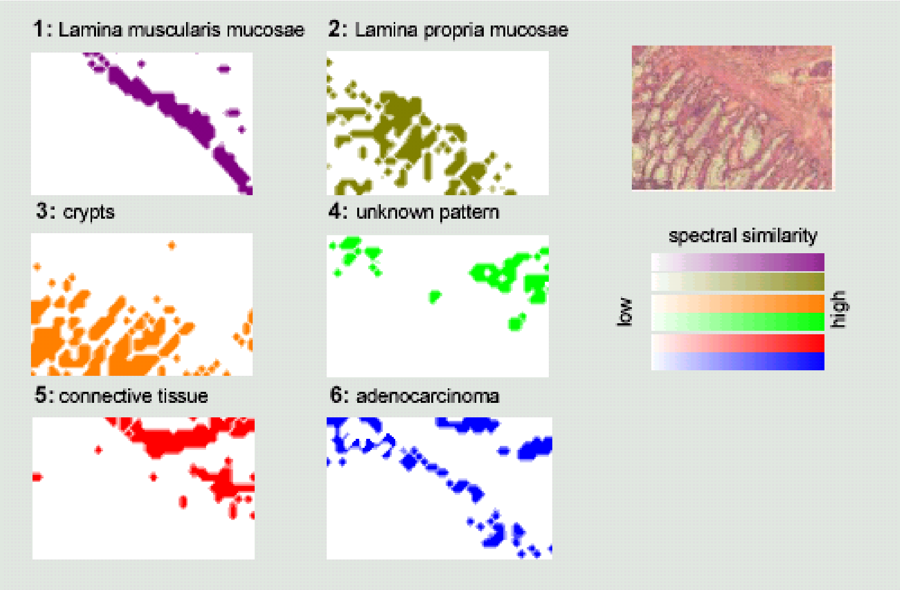
Use computer-based pattern recognition techniques to assign various regions to a particular bio-tissue. Unlike classical spectroscopy, IR spectrum in finger-print regions displays very broad features, thus, computer-based recognition techniques are essential (c.f. speech recognition).

1) some parameterization algorithm that converts entire waveform to a vector of dimension, N.

2) ascribe this vector to other known materials in the database.

Recognizing patterns





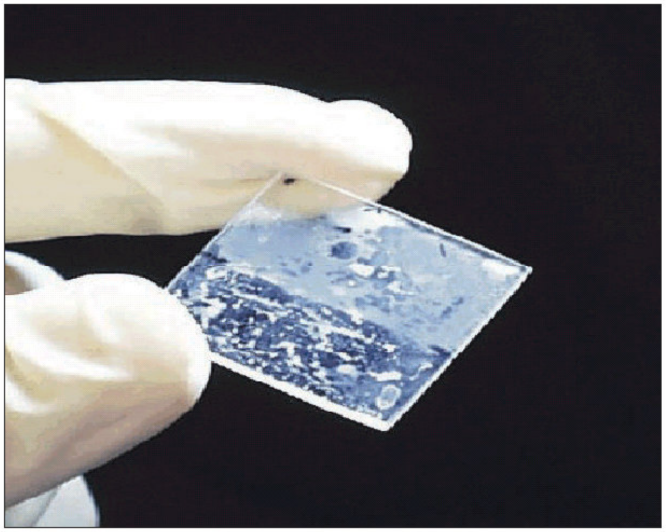
Biomaterial Applications

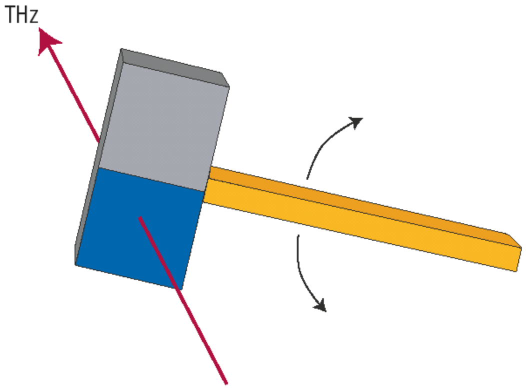
- DNA structures have helix, base twisting, and librational modes in the 20 – 100 cm^{-1} range
- Sample has to be very dry otherwise humidity becomes a factor (H_2O absorption at 1 THz is 235 cm^{-1})
- There is a clear difference in refractive index in THz range for hybridized and denatured DNA
- Detection of DNA mutation of a single base pair with femtomole sensitivity has been demonstrated
- There is an effort to develop "label-free" T-ray biosensor (as opposed to biochips)

Nagel et al. in Appl. Phys. Let. 2002, "Integrated THz technology for label-free genetic diagnostics"

T-ray biosensors?

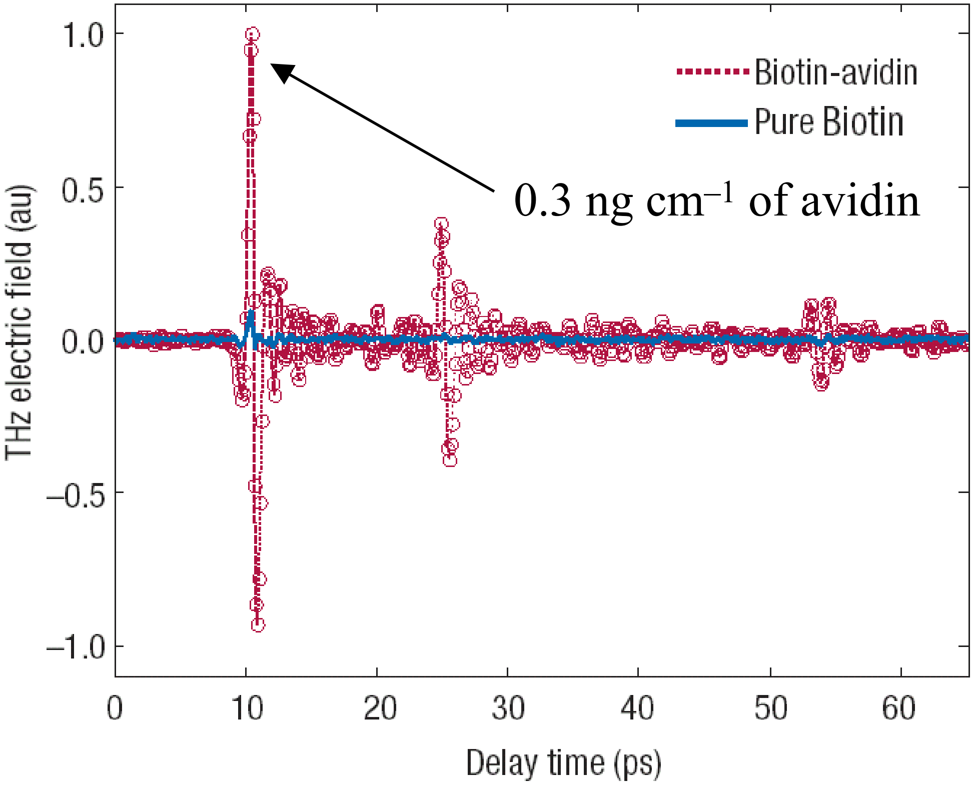
Mickan et al. in Phys. Med. Biol 2002, “Label-free bioaffinity detection using THz technology”





Ferguson and Zhang in Nature 2002
“Materials for THz science and technology”

Differential THz-TDS: SNR up to 10^8



0.3 ng cm^{-1} of avidin

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High-T$_c$ Superconductor Studies Using THz-TDS

Kaindl et al., in Phys. Rev. Let. 2002

“Far-Infrared Optical Conductivity Gap in Superconducting MgB$_2$ Films”

- Measurement of superconducting energy gap (5 meV for MgB$_2$, for T$_c$~39K)
- Magnetic penetration depth

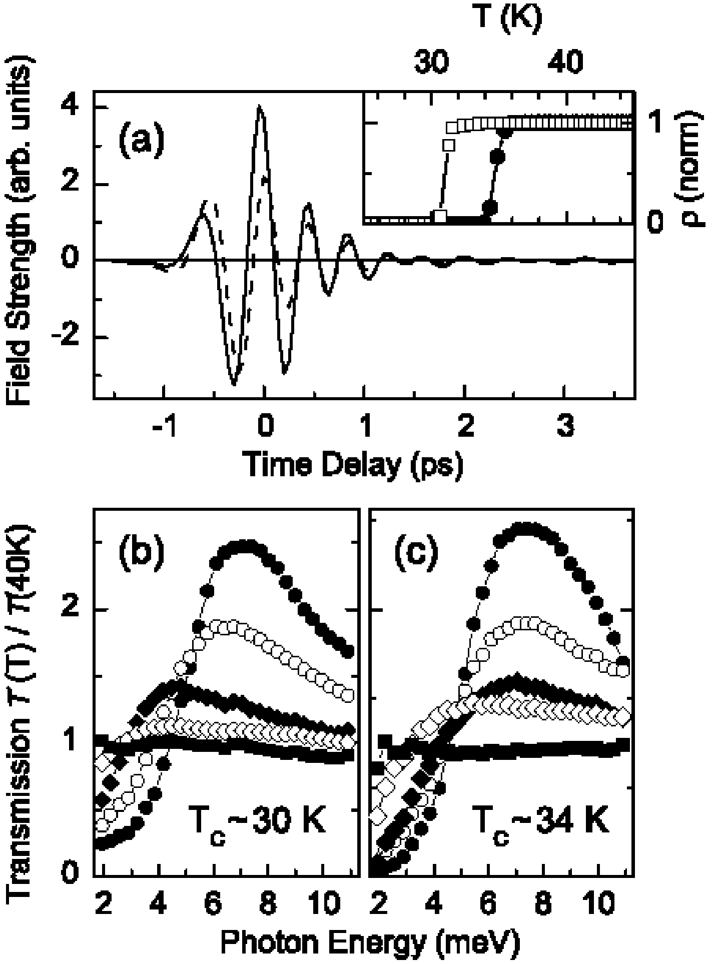


FIG. 1. (a) Electric field transients transmitted through the 100 nm MgB$_2$ film at $T = 6$ K (solid line) and 40 K (dashed line). Inset: resistance of the 200 nm (dots) and 100 nm (open squares) film corresponding to $\rho(40\text{ K}) \approx 10$ and 100 $\mu\Omega$ cm, respectively. (b) Transmission $\mathcal{T}$ normalized to $\mathcal{T}(40\text{ K})$ as obtained from the transients for the 100-nm-thick film at $T = 6$ K (dots), 20 K (open circles), 27 K (solid diamonds), 30 K (open diamonds), and 33 K (solid squares). (c) Results for the 200-nm-thick film at $T = 6$ K (dots), 20 K (open circles), 25 K (solid diamonds), 30 K (open diamonds), and 36 K (solid squares).

THz Hall Effect Study of Semiconductors

- Hall effect is the method of choice for measuring DC properties of thin doped epitaxial layers of semiconductors
- Uses the so-called "4-point probe" method (cf. complex conductivity tensor measurements)
- Contact resistance is an issue

- Instead, T-rays serve as applied E-field. Sample reradiates (Hall-field) in different polarization. Measure the two polarizations.
- Use Drude model to infer carrier density N and mobility μ with 250 µm spatial resolution (~ order of magnitude smaller than is achievable with best 4-point probe method).

THz Hall Effect Study of Semiconductors

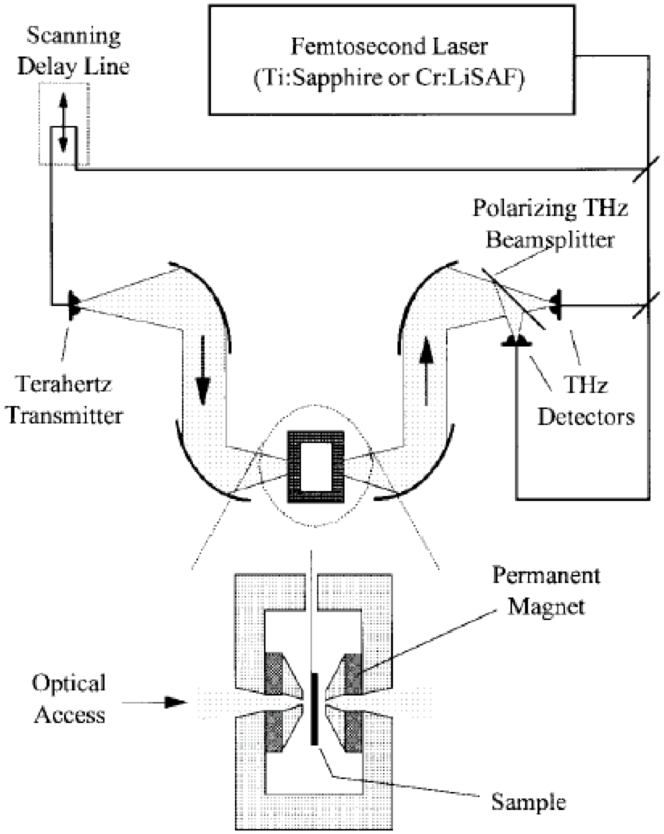
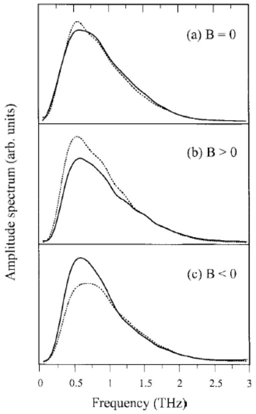


Fig. 13. Schematic of the setup used for terahertz Hall effect measurements, showing permanent 1.3-T magnet, free-standing wire grid polarizing beam splitter, and two receivers operating in parallel for simultaneous detection of two orthogonal polarizations.



Mittleman et al. in IEEE Quantum Elect. 1996 “T-ray imaging”

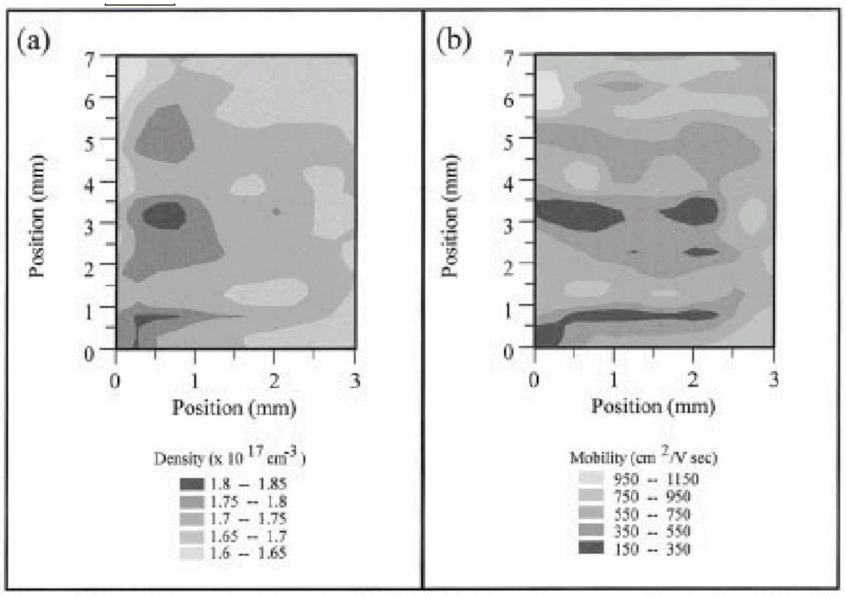


Fig. 15. Terahertz images of the sample from Fig. 14, generated as described in the text. Variations in the doping density are shown in (a), while (b) shows inhomogeneities in the carrier mobility. In each case, the legends show the relation between the color scale and the calculated parameter values.

ERL as THz source

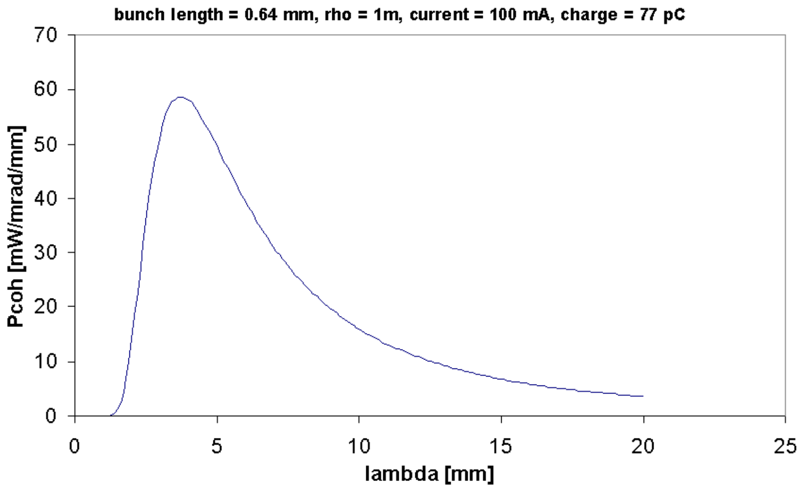
- Power levels
- Dedicated THz source

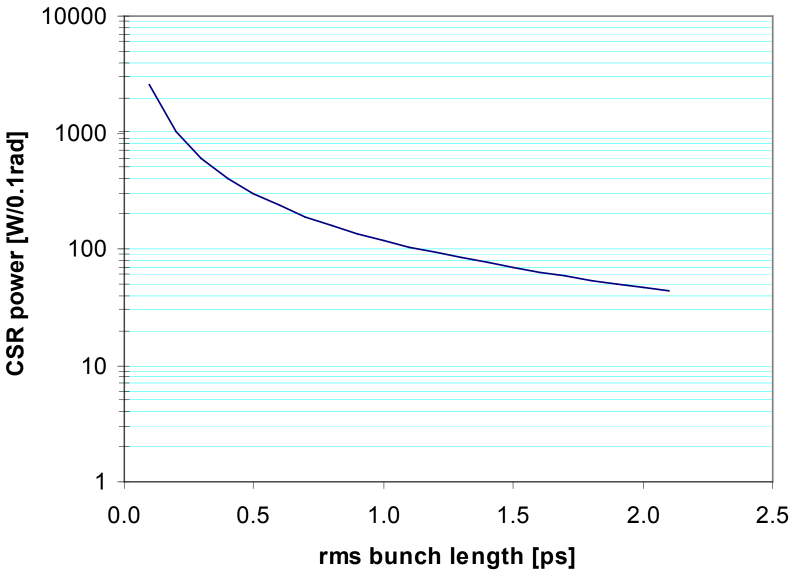
Power levels

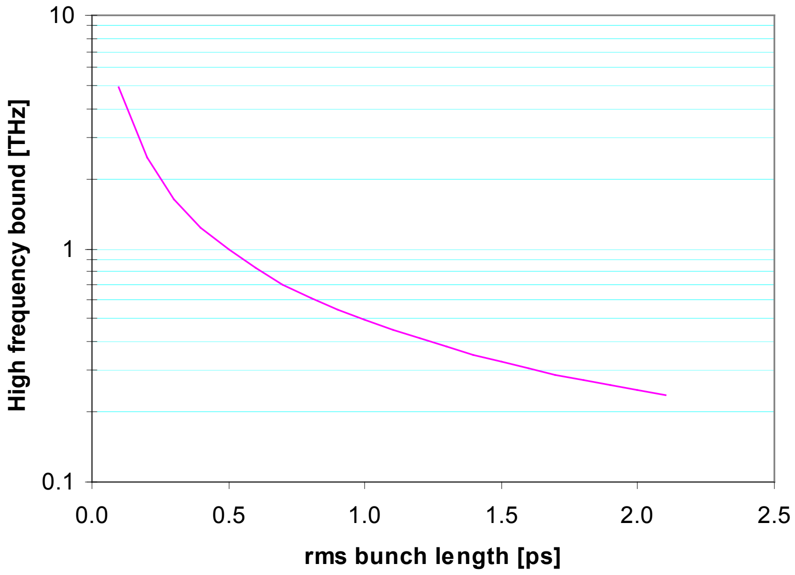
- Assuming Gaussian profile (the worst case)

$$P^{(N)}_{\text{coh}} = \frac{1}{4\pi\varepsilon_0}\frac{N^2e^2c}{\rho^2}\left(\frac{\sqrt{3}}{\sigma_\alpha}\right)^{4/3}\times\frac{1}{2\pi\sqrt{3}}\left[\Gamma(2/3)\right]^2$$

$$U_d[\text{eV}] = 198\frac{q[\text{pC}]}{\sigma_z[\text{mm}]^{4/3}}\rho[\text{m}]^{1/3}\frac{\theta_d[\text{deg}]}{360^\circ}$$







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Dedicated THz Source

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Dedicated THz Source

- Don't need high energy (injector part is enough)

Dedicated THz Source

- Don’t need high energy (injector part is enough)
- Generate spiked longitudinal profile
  to reach higher THz frequency

Dedicated THz Source

- Don’t need high energy (injector part is enough)
- Generate spiked longitudinal profile
  to reach higher THz frequency
- Wiggler / undulator can be used to
  reach higher THz frequency range
  more efficiently in OK FEL configuration

Dedicated THz Source

- Don’t need high energy (injector part is enough)
- Generate spiked longitudinal profile
  to reach higher THz frequency
- Wiggler / undulator can be used to
  reach higher THz frequency range
  more efficiently in OK FEL configuration

Conclusion: THz light production is easy!