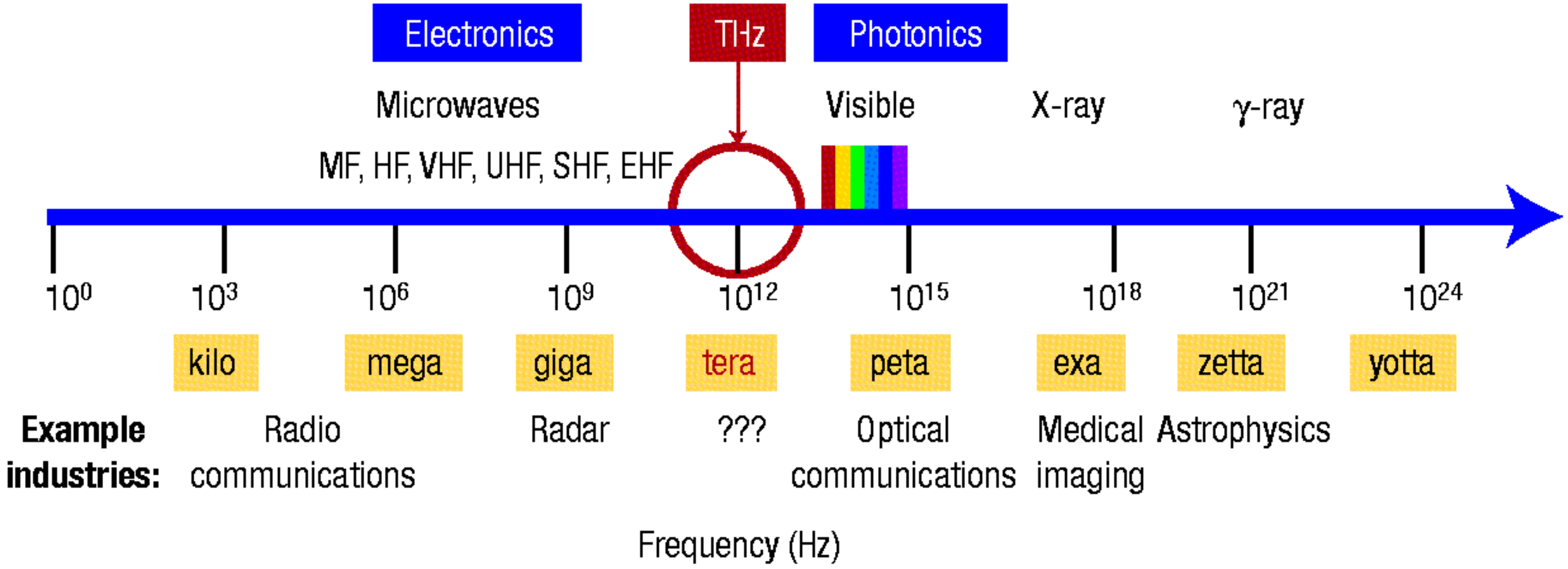
THz Radiation: Opportunity with ERL Prototype (Part II)

Contents:

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

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”

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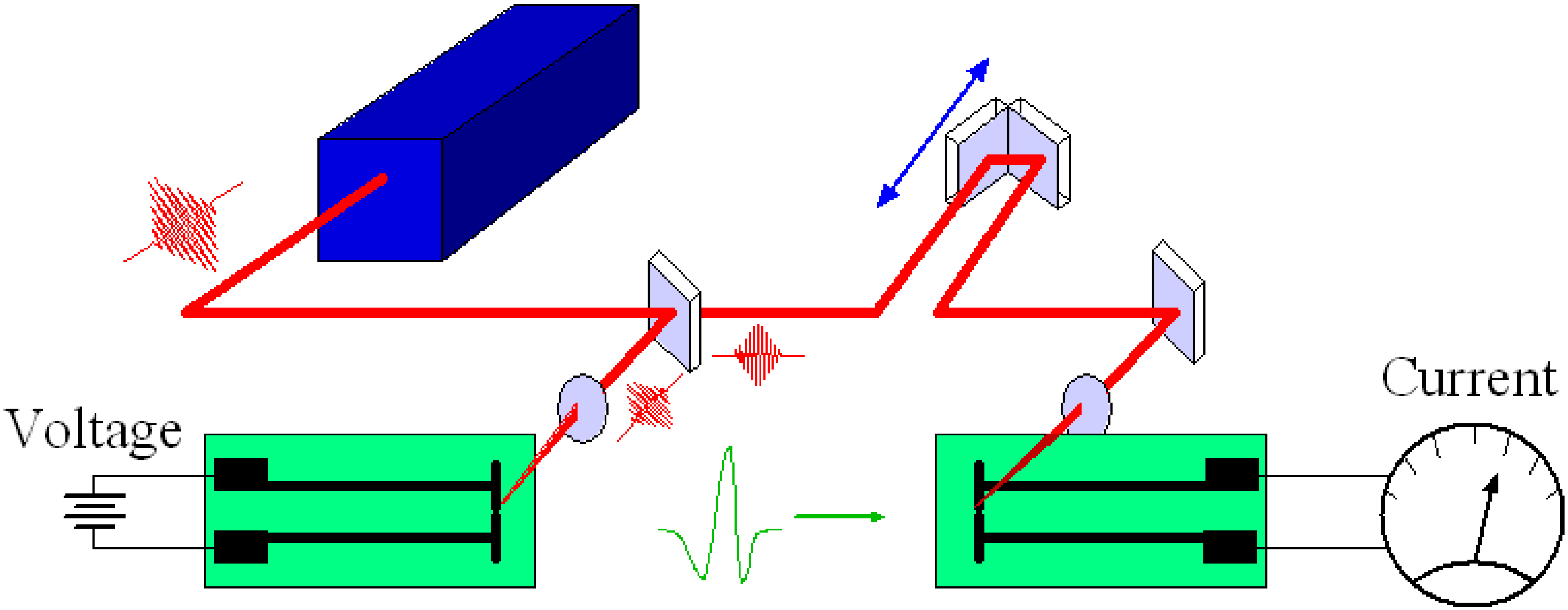
THz-TDS



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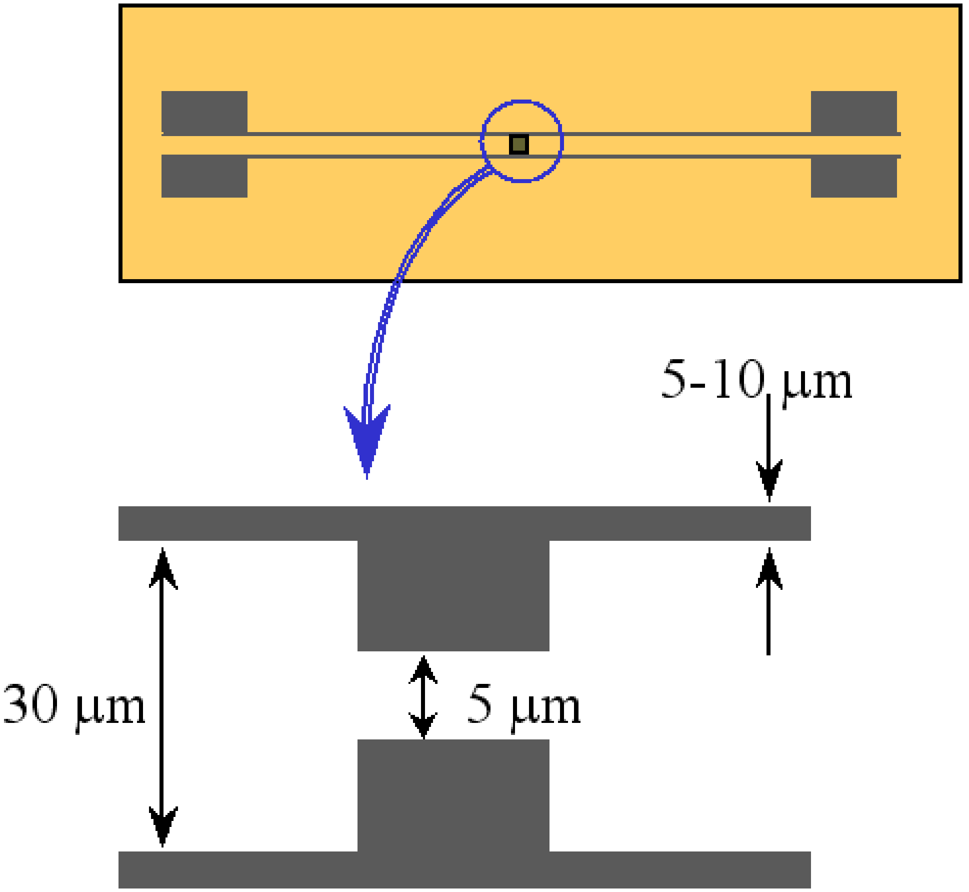
THz-TDS: "Coherent" Detection

THz Detector



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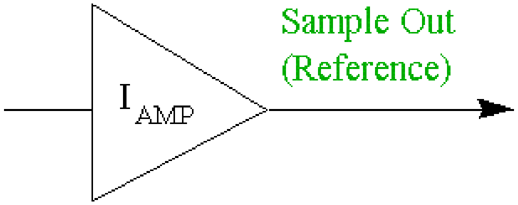
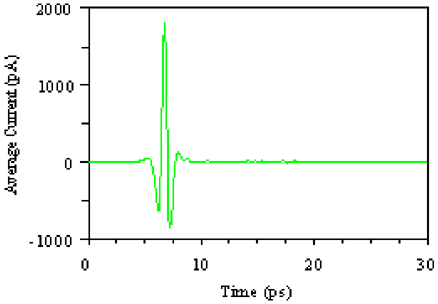
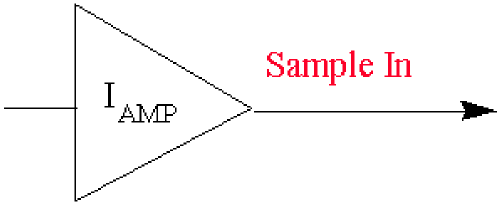
THz-TDS: Signal Processing

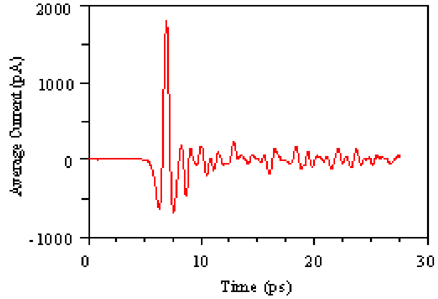


Sample Out
(Reference)

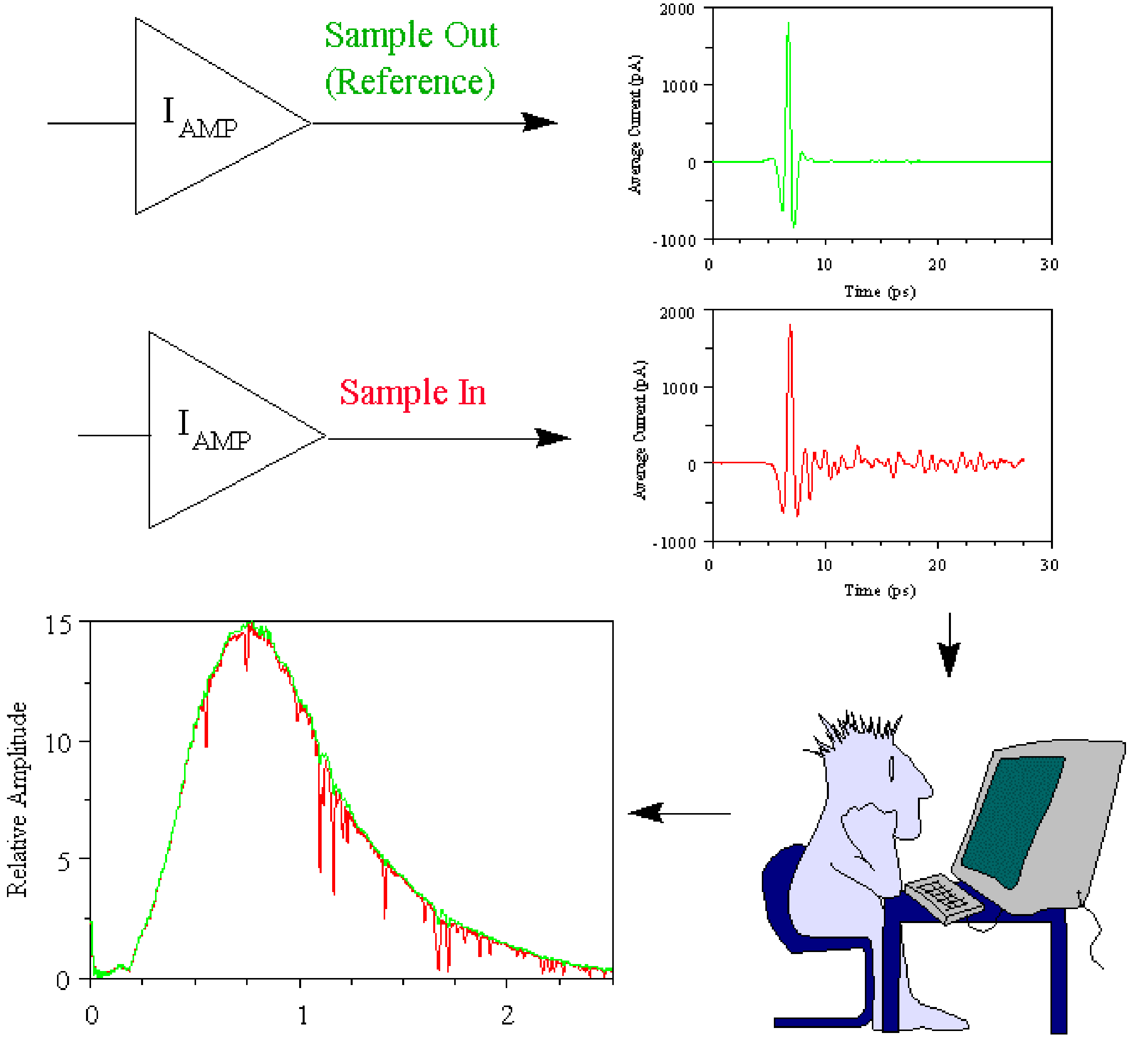




Sample In



THz-TDS: Signal Processing



Sample Out
(Reference)

Sample In

Numerical Fast Fourier Transform

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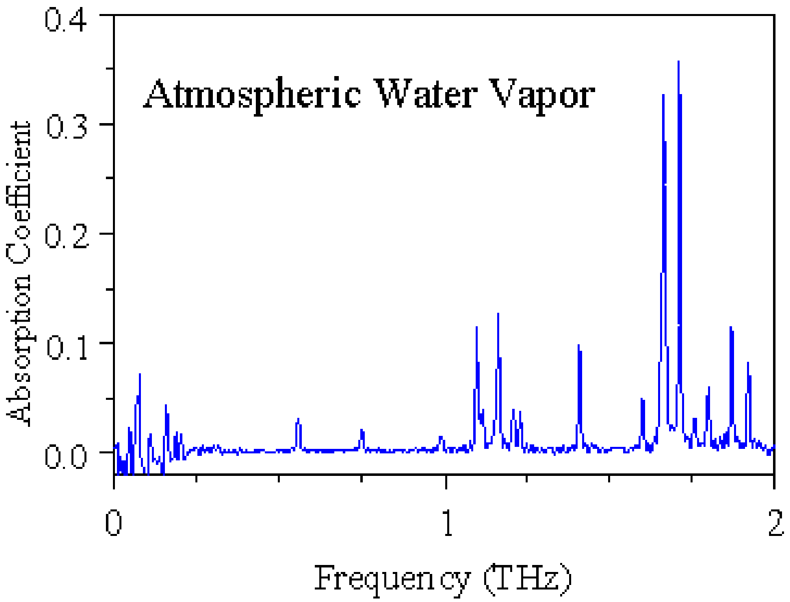
Water Vapor Spectrum



$$E_s(\omega)/E_r(\omega) = \underset{\textit{Amplitude}}{e^{-k''(\omega)z}} \quad \underset{\textit{Phase}}{e^{i[k'(\omega)+k_o(\omega)]z}}$$

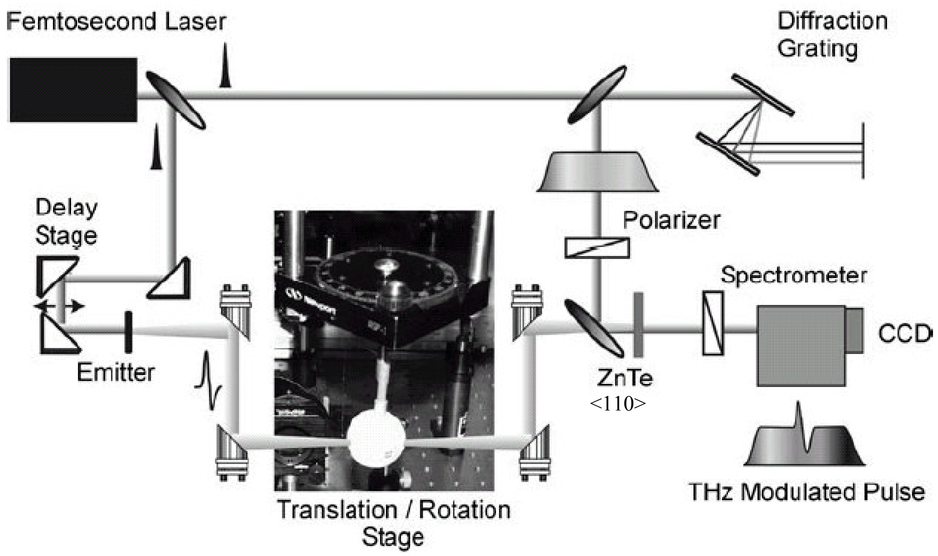
$$k(\omega) = k' + ik'' \qquad k_o = 2\pi/\lambda$$

absorption and index

Applications

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

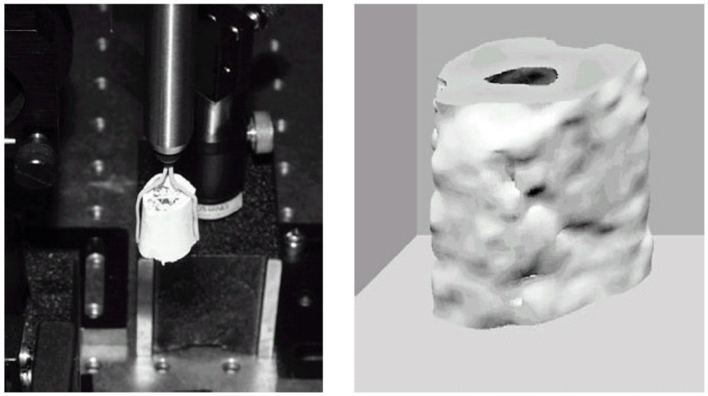
THz Imaging using electro-optic detection



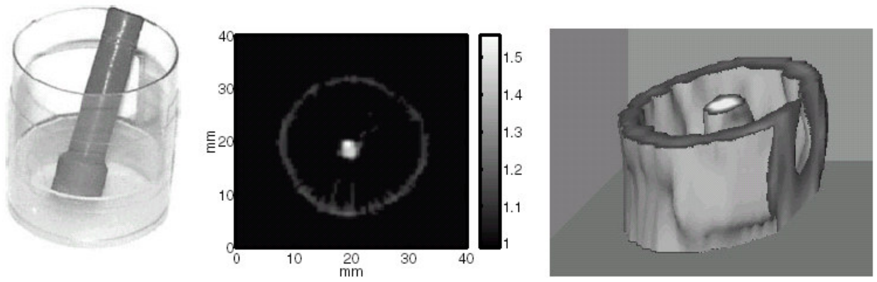
Ferguson, et al. in Phys. Med. Biol. 2002
“Towards functional 3D T-ray imaging”

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)

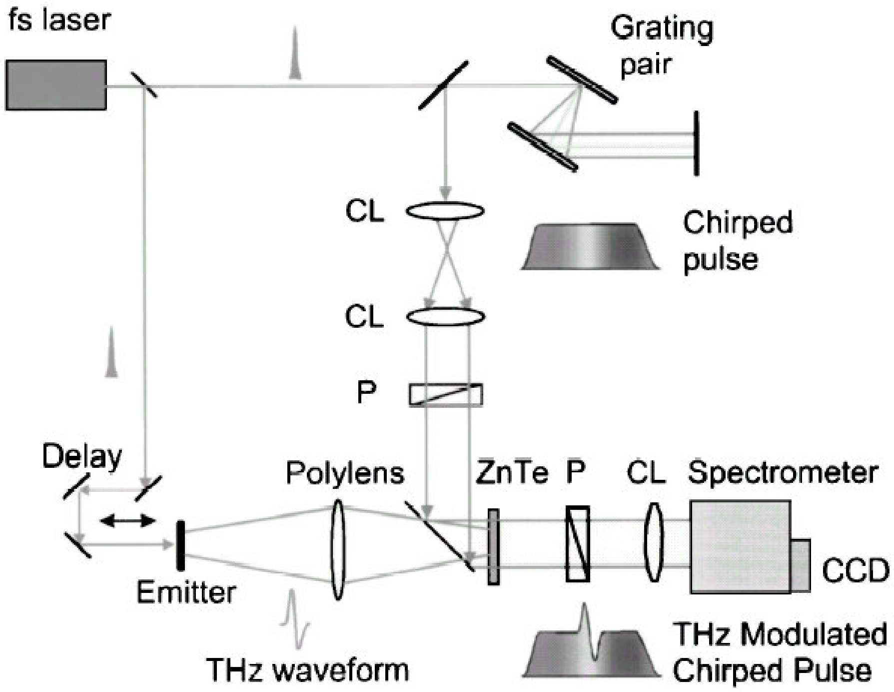
turkey bone



(a) (b) (c)

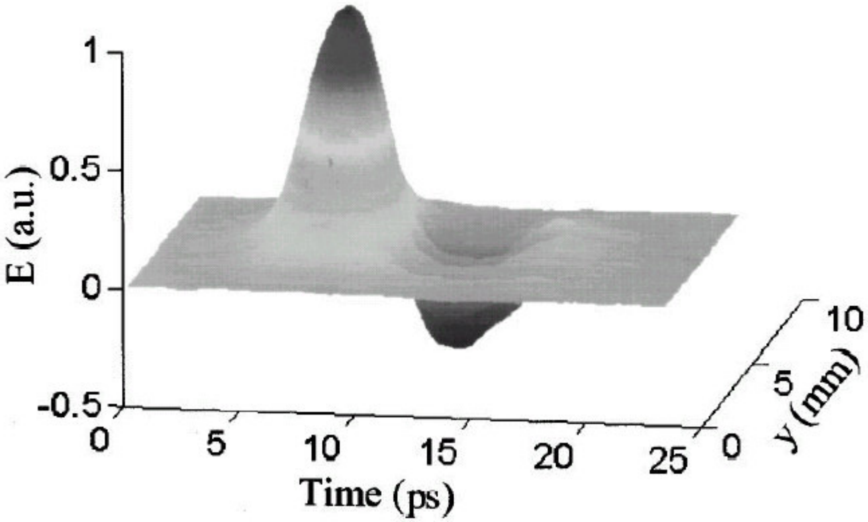
vial and plastic tube

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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$$$ Images $$$

$$$ Images $$$

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$$$ Images $$$

Can you see a gun?

$$$ Images $$$

What about knife?

Can you see a gun?

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)

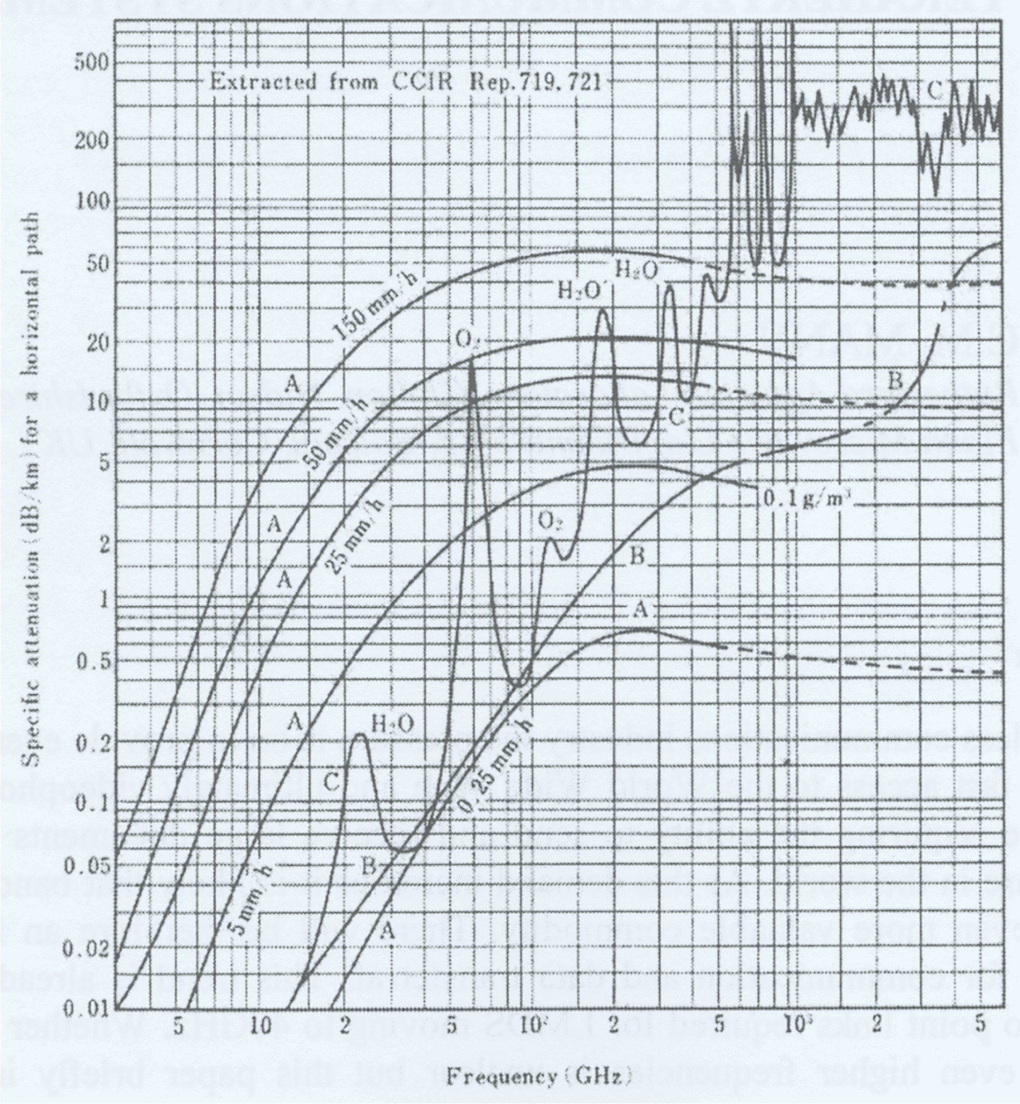
THz Communication

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)

Absorption Spectrum for Atmosphere



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 can 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

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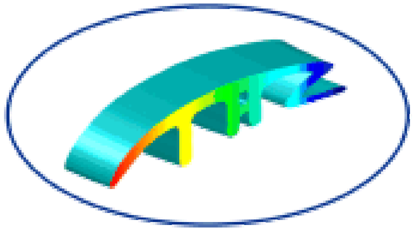
Biomedical Applications: Exposure Limits

- 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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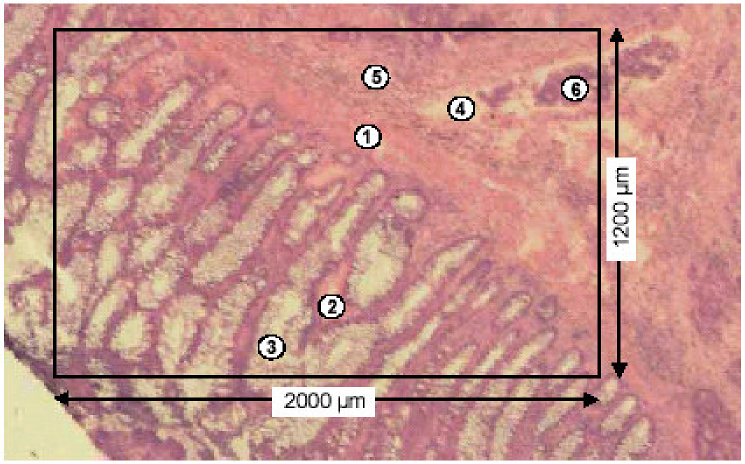
Biomedical Application Example

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



1: L. muscularis mucosae

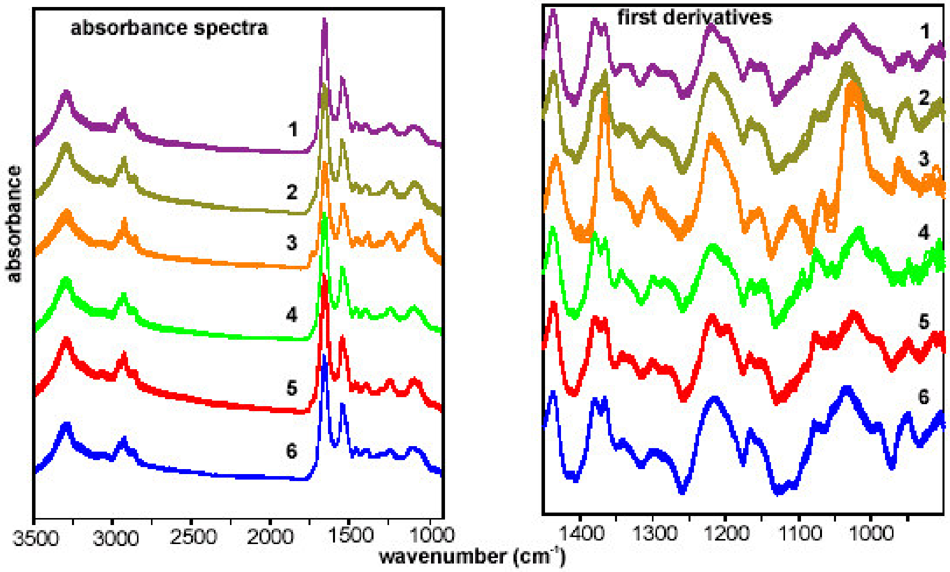
2: L. propria mucosae

3: crypts

4: unknown structure

5: connective tissue

6: adenocarcinoma



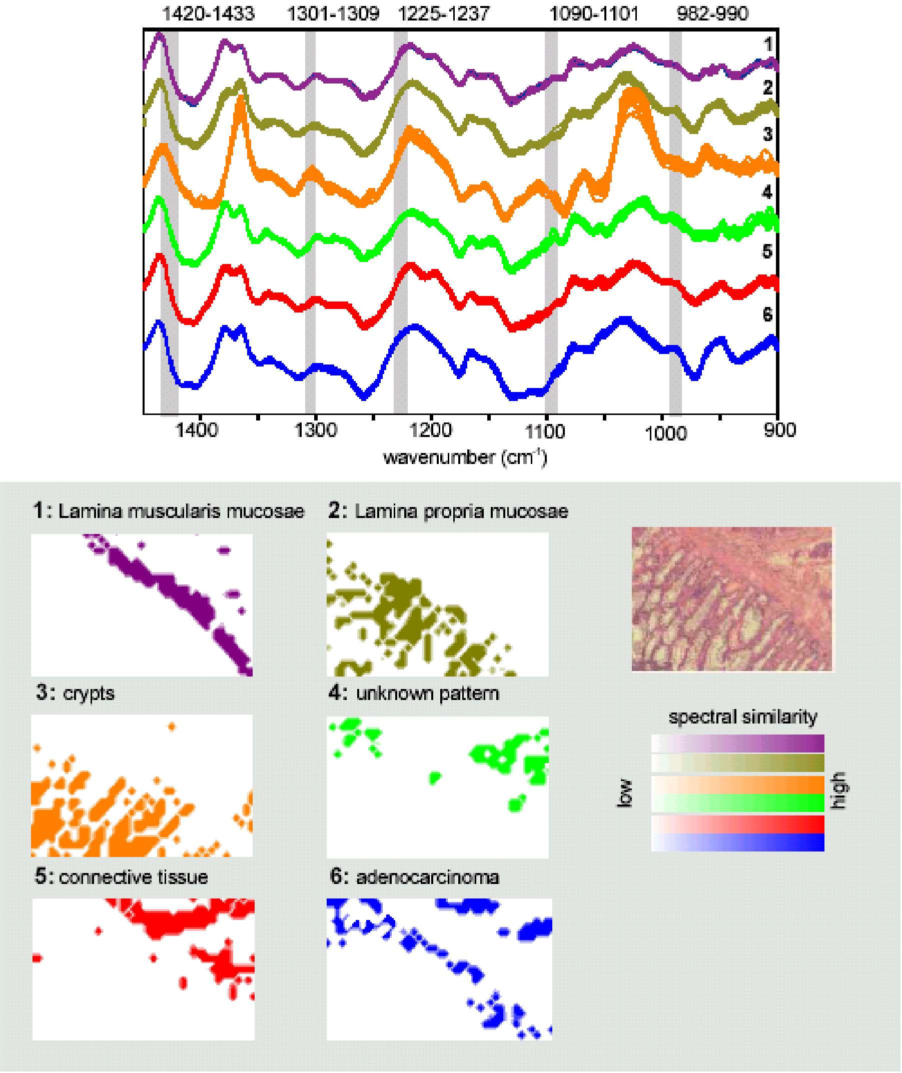
Basic idea:

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



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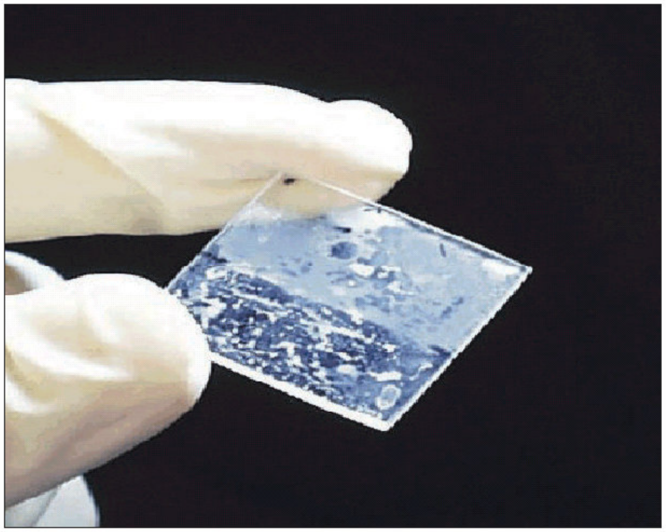
Biomaterial Applications

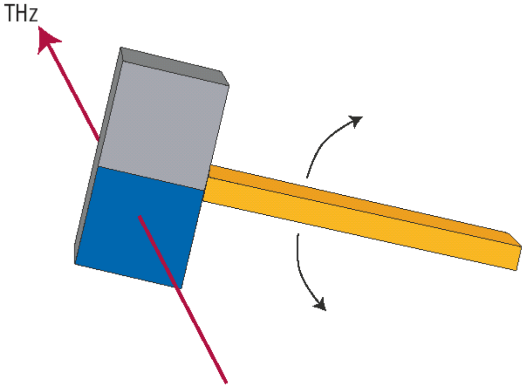
- DNA structures have helix, base twisting, and librational modes in the 20 – 100 cm^{-1} range
- Sample has to be very dry otherwise humidity becomes a factor (H_2O absorption at 1 THz is 235 cm^{-1})
- There is a clear difference in refractive index in THz range for hybridized and denatured DNA
- Detection 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?

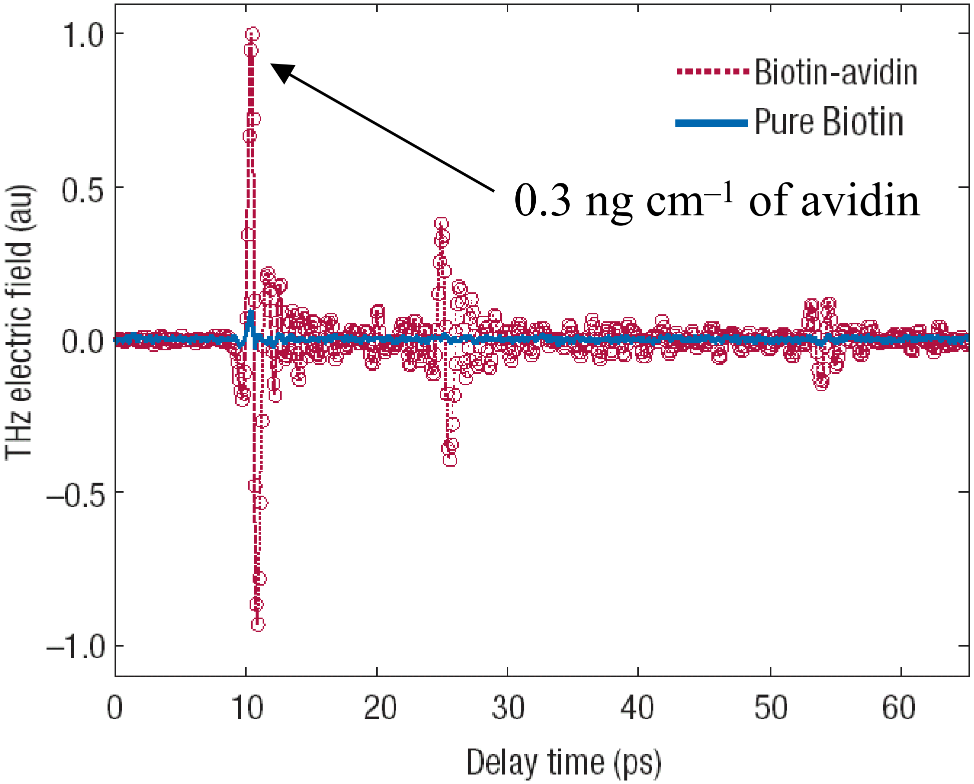
Mickan et al. in Phys. Med. Biol 2002, “Label-free bioaffinity detection using THz technology”





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

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

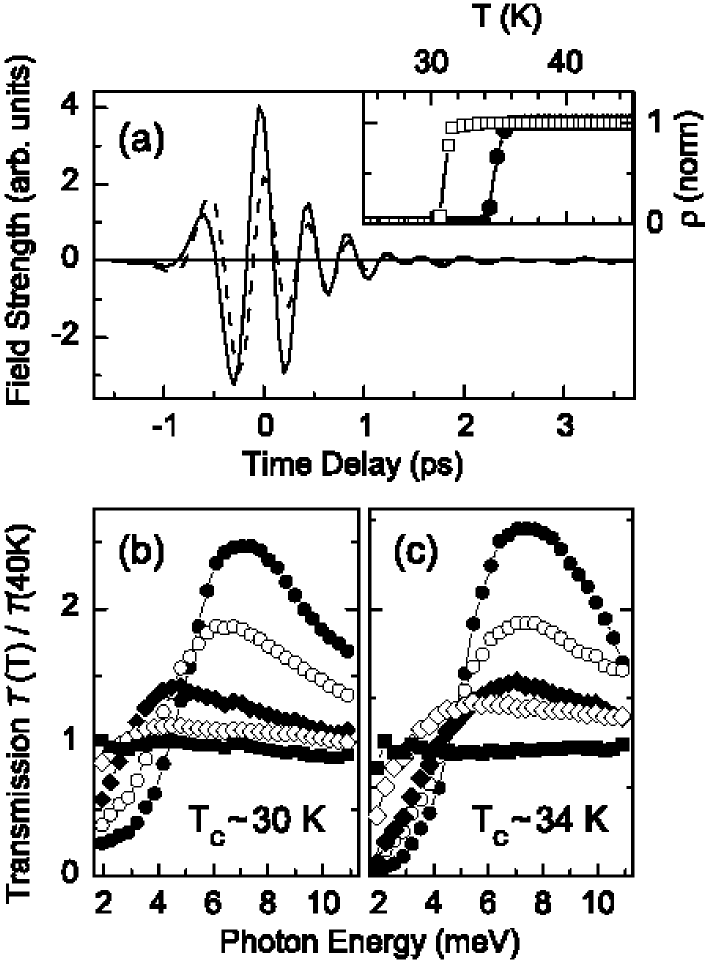


FIG. 1. (a) Electric field transients transmitted through the 100 nm MgB_2 film at $T = 6$ K (solid line) and 40 K (dashed line). Inset: resistance of the 200 nm (dots) and 100 nm (open squares) film corresponding to $\rho(40\text{ K}) \approx 10$ and 100 $\mu\Omega$ cm, respectively. (b) Transmission $\mathcal{T}$ 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

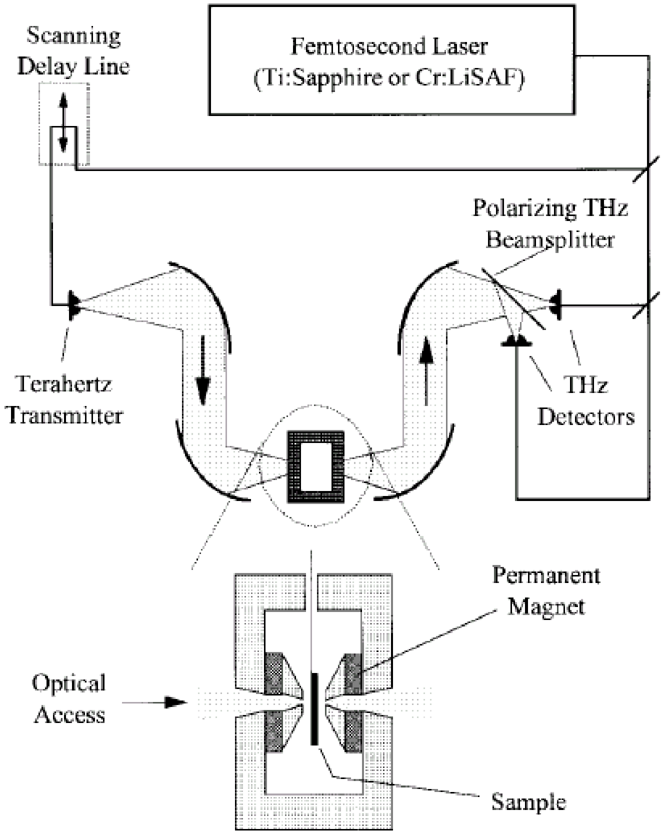
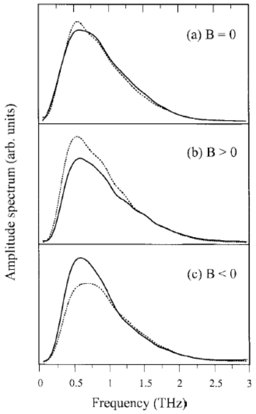


Fig. 13. Schematic of the setup used for terahertz Hall effect measurements, showing permanent 1.3-T magnet, free-standing wire grid polarizing beam splitter, and two receivers operating in parallel for simultaneous detection of two orthogonal polarizations.



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

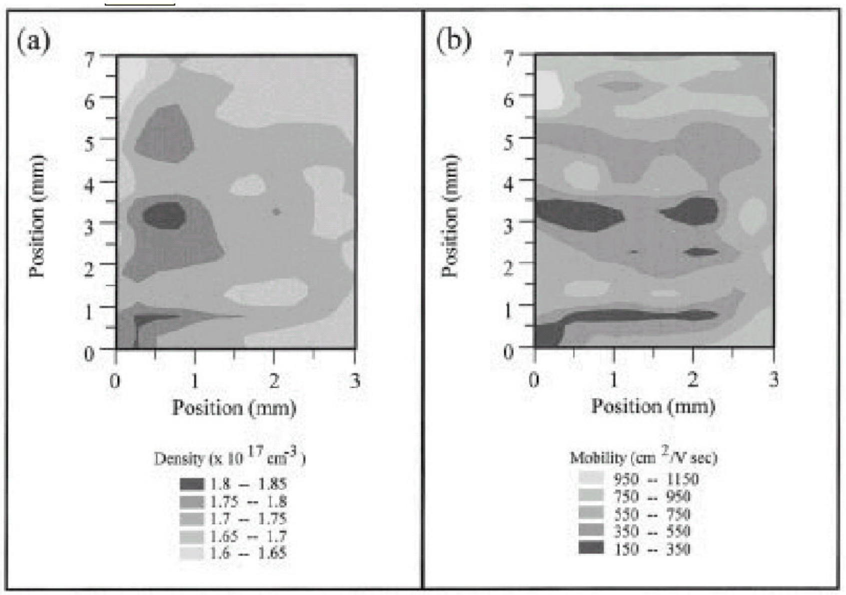


Fig. 15. Terahertz images of the sample from Fig. 14, generated as described in the text. Variations in the doping density are shown in (a), while (b) shows inhomogeneities in the carrier mobility. In each case, the legends show the relation between the color scale and the calculated parameter values.

ERL as THz source

- High CW power levels available (hundreds of W)
- 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)
- Dedicated THz source

Radiation from a Bend Magnet

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

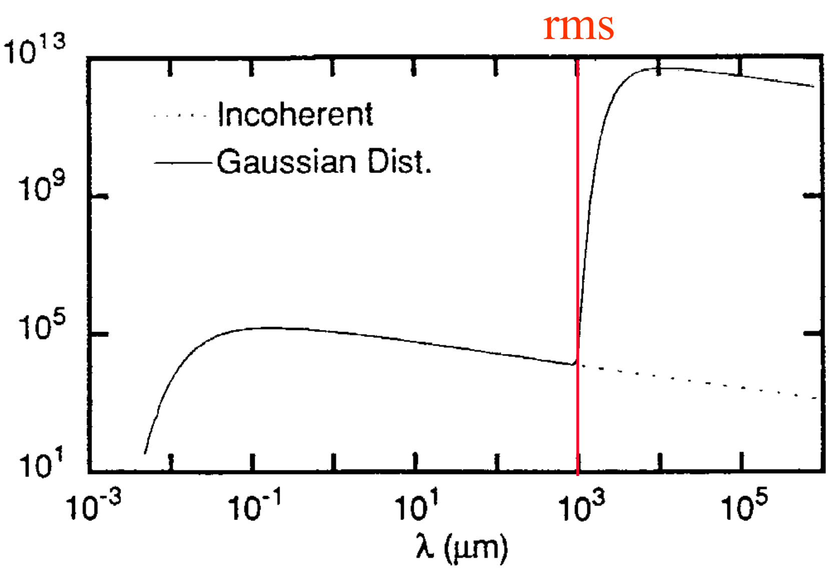
Form factor

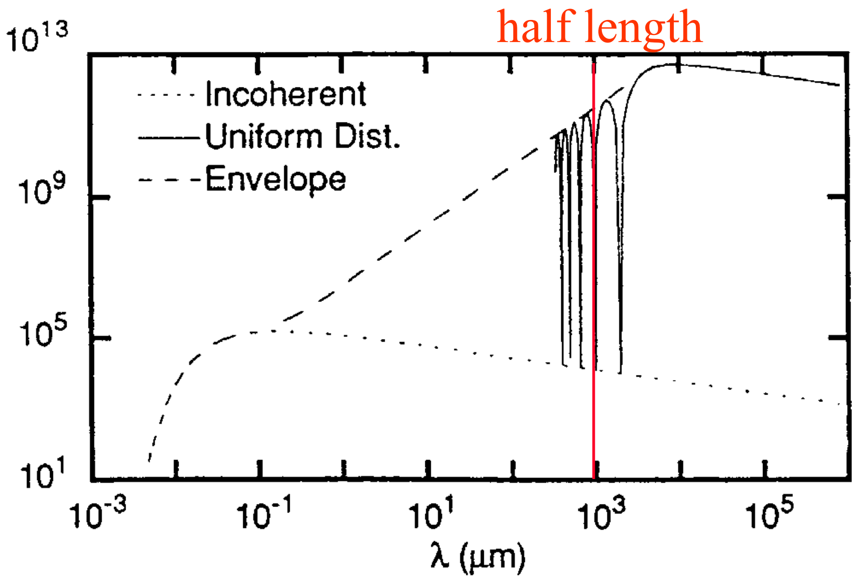
Gaussian

$$f(\omega) = \exp\left(-4\pi^2 \sigma^2 / \lambda^2\right)$$

Uniform

$$f(\omega) = \mathrm{sinc}^2 (2\pi l / \lambda)$$



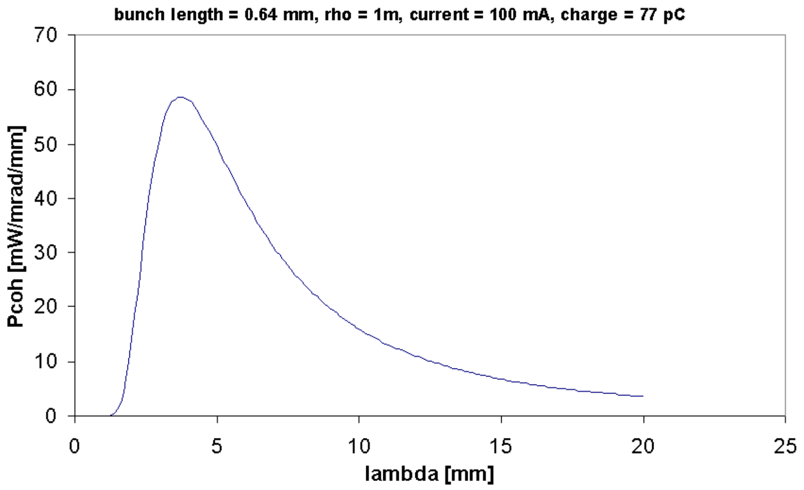


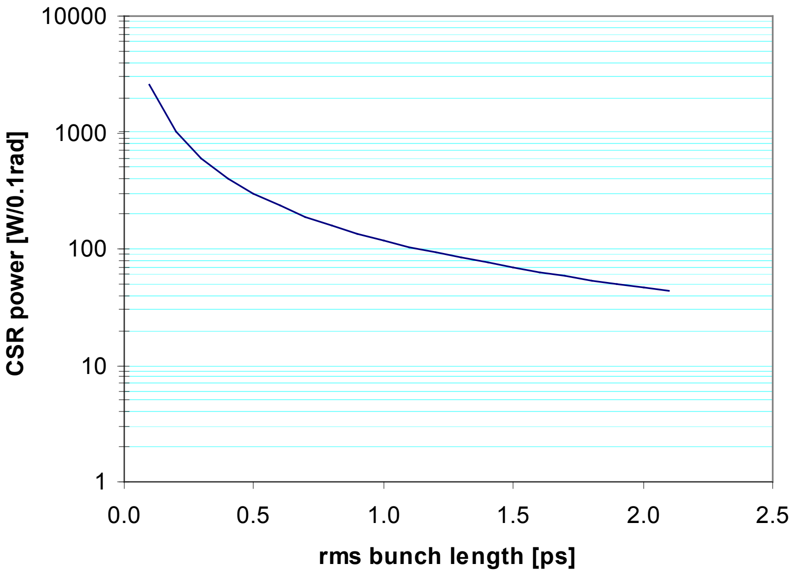
Power levels

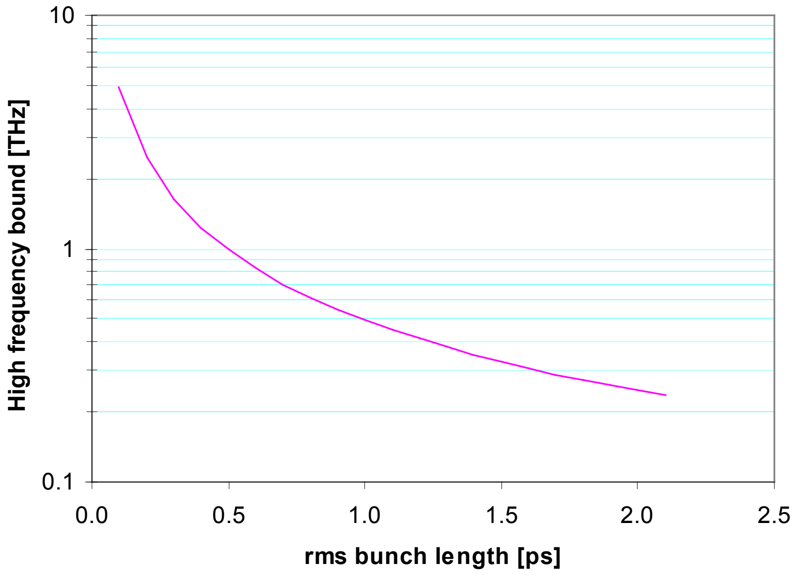
- Assuming Gaussian profile (the worst case)

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

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







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Dedicated THz Source

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Conclusion: THz light production is easy!

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