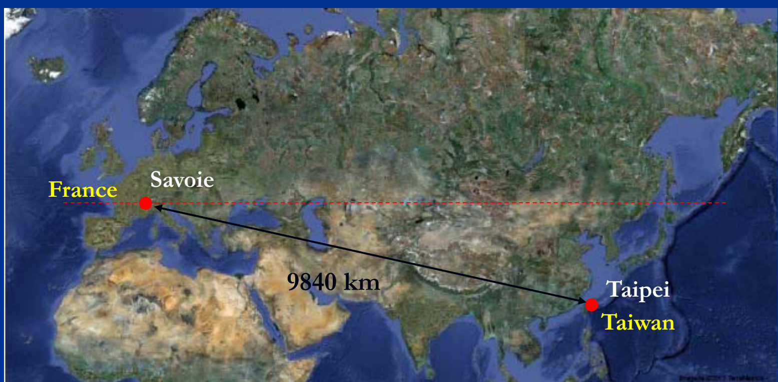
Where is Savoie?

Savoie = Savoy (in English)



2

Where is Savoie?

3

Outline of the seminar

- What is the THz domain of the electromagnetic spectrum?
- Why is it so popular in present research works?
- Physics with THz
  - Techniques
  - Interaction matter-THz

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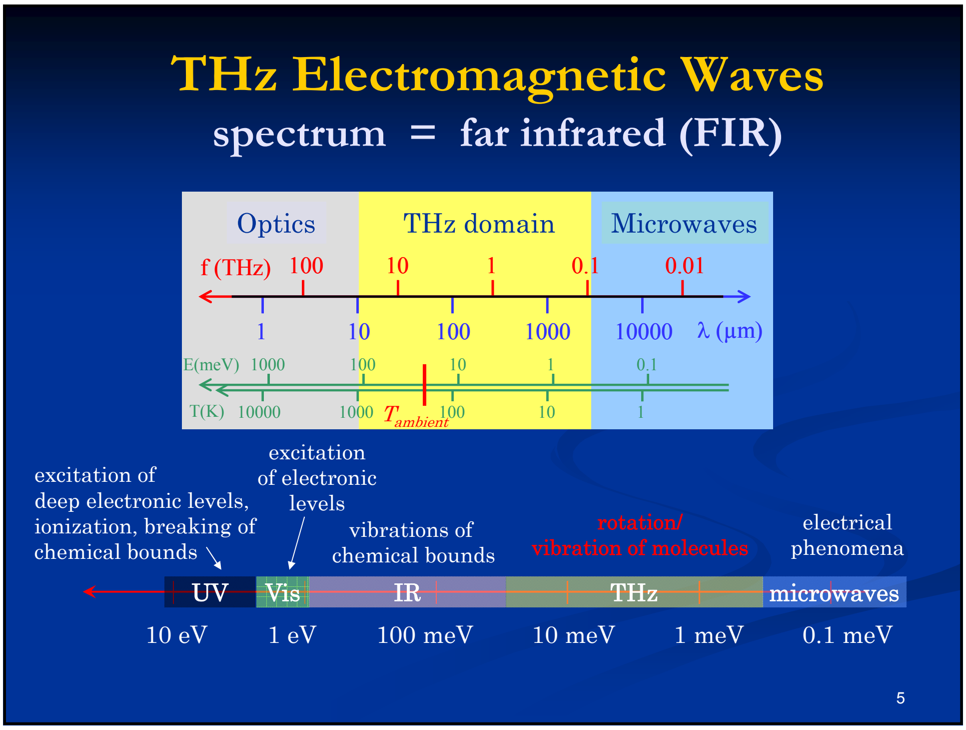
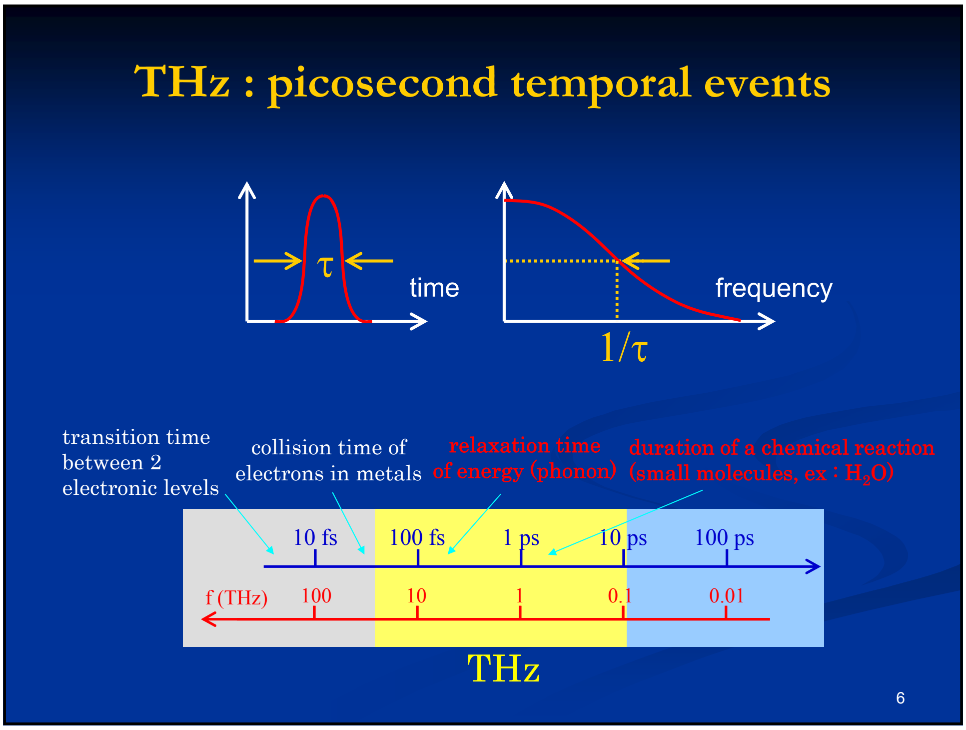

THz Electromagnetic Waves
spectrum = far infrared (FIR)
Optics
THz domain
Microwaves
f (THz) 100 10 1 0.1 0.01
1 10 100 1000 10000 λ (µm)
E(meV) 1000 100 10 1 0.1
T(K) 10000 1000 100 10 1
T ambient
excitation of deep electronic levels, ionization, breaking of chemical bounds
excitation of electronic levels
vibrations of chemical bounds
rotation/ vibration of molecules
electrical phenomena
UV
Vis
IR
THz
microwaves
10 eV 1 eV 100 meV 10 meV 1 meV 0.1 meV
5


THz : picosecond temporal events
τ
time
frequency
1/τ
transition time between 2 electronic levels
collision time of electrons in metals
relaxation time of energy (phonon)
duration of a chemical reaction (small molecules, ex : H2O)
10 fs 100 fs 1 ps 10 ps 100 ps
f (THz) 100 10 1 0.1 0.01
THz
6

Why THz EM waves are so interesting?

Some THz-related phenomena

- Electrons in highly-excited atomic Rydberg states orbit at THz frequencies
- Small molecules rotate at THz frequencies
- Collisions between gas phase molecules at room temperature last about 1 ps
- Biologically-important collective modes of proteins vibrate at THz frequencies
- Frustrated rotations and collective modes cause polar liquids (such as water) to absorb at THz frequencies
- Electrons in semiconductors and their nanostructures resonate at THz frequencies
- Superconducting energy gaps are found at THz frequencies
- An electron in Intel's THz transistor races under the gate in ~1 ps
- Gaseous and solid-state plasmas oscillate at THz frequencies
- Matter at temperatures above 10 K emits black-body radiation at THz frequencies…

Some involved techniques and technologies

- Solid-state electronics
- Vacuum electronics
- Microwave techniques
- Ultrafast visible and NIR lasers
- Single-mode continuous-wave NIR lasers
- Electron accelerators ranging in size from a few inches to a mile-long linear accelerator at SLAC
- Novel materials…

and Applications (see coming slides) !

From Report of a DOE-NSF-NIH Workshop held February 12 – 14, 2004, Arlington, VA
M. S. Sherwin, C. A. Schmuttenmaer, and P. H. Bucksbaum, Editors

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Why studying the THz domain? Medicine

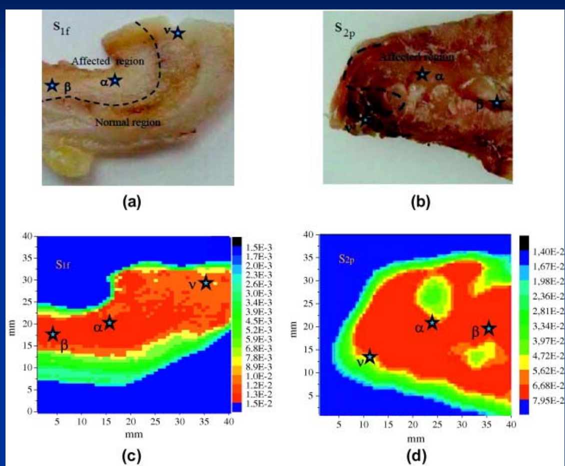

Fig. 6. Samples that have been imaged by CWTI at the wavelength λ = 393 µm (ν = 0.76 THz): (a and b); CWTI absorption coefficient images of the samples: (c and d). The reddish areas, corresponding to stronger absorption, correlate well with the cancer affect regions previously determined by histological observation. The green-yellow spots in red area of (d) have smaller thickness caused by paraffin embedding process

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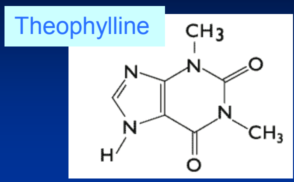
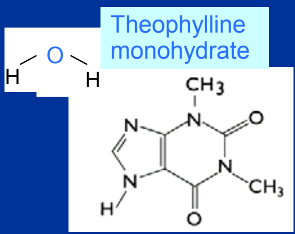
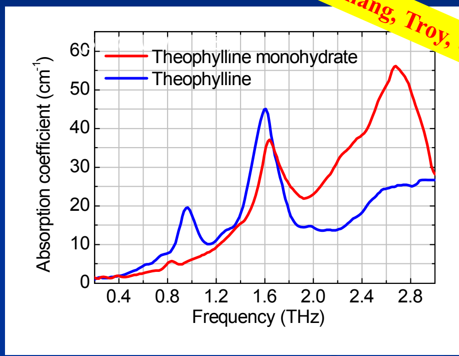
Why studying the THz domain? Chemical analysis

Slide from X-C Zhang, Troy, USA







Theophylline is used as an oral bronchodilator for asthma therapy by millions of people everyday. However, it is always a difficulty to judge whether it is hydrated or anhydrous before companies sell it or patients take it (anhydrous drugs will transfer to hydrated ones when they are processed or stored in ambient air).

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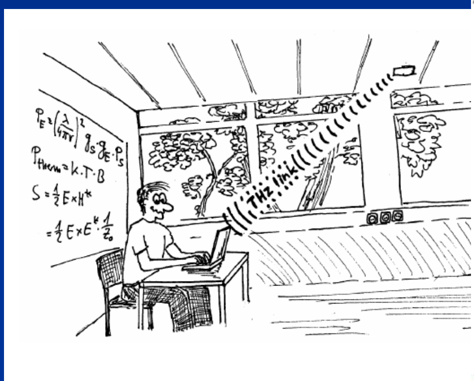
Why studying the THz domain? Telecoms



The goal of THz telecoms as dreamed by Martin Koch, Marburg, Germany

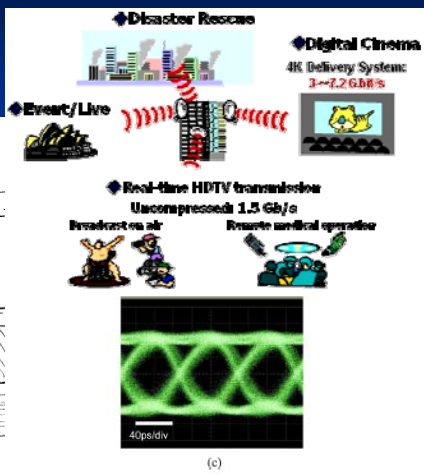


Fig. 3. (a) Experimental setup for data transmission link at 300 GHz (LD: laser diode; EOM: electrooptic modulator; PPG: pulse pattern generator; EDFA: erbium doped fiber amplifier; UTC-PD: uni-traveling photodiode; SBD: Schottky barrier diode; LNA: low noise amplifier; ED: error detector; OSC: oscilloscope). (b) Measured BERs. (c) Eye diagram at 16-Gb/s data rate.

Results from T. Nagatsuma
Osaka University

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Why studying the THz domain? Environment

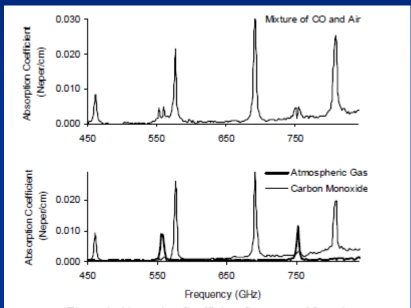

Figure 1: Absorption Coefficient Spectrum of Samples

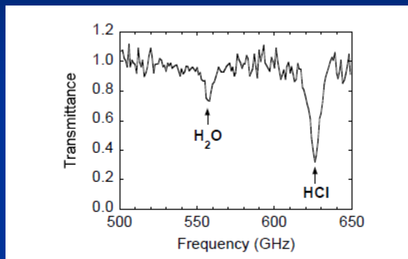

Fig. 3: Absorption spectrum of smoke produced from PVC heated to 350 degree Celsius.

Identification of Pollutant Gases from an Atmospheric Mixture Using High Resolution Dispersive Fourier Transformation Spectroscopy
Nawaf N. Almoayed[1], *Student Member, IEEE*, Golam R. Khan[1], *Student Member, IEEE*, Mohammed N. Afsar[1], *Fellow, IEEE*

Absorption spectra of hydrogen chloride and carbon monoxide in smoke
Naofumi Shimizu[a], Ken Matsuyama[b], and Iwao Hosako[a]

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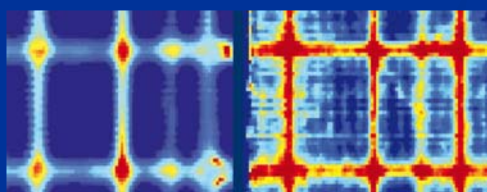
Why studying the THz domain? Industry



Fraunhöfer Institute in Kaiserslautern

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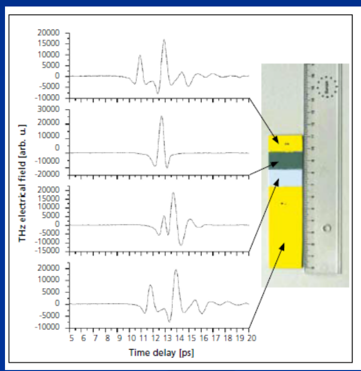
Why studying the THz domain? Industry



Analysis of the paint coating of airplane propellers
Fraunhofer Kaiserslautern

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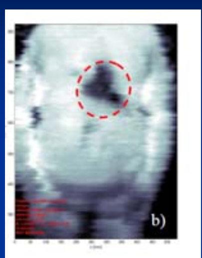
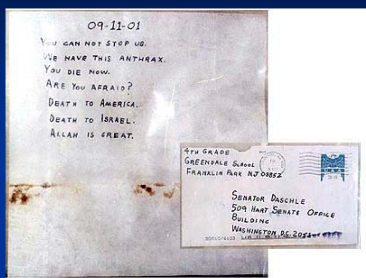
Why studying the THz domain? Security



0.1-1 THz
Image
VTT Finland



300-GHz imaging system

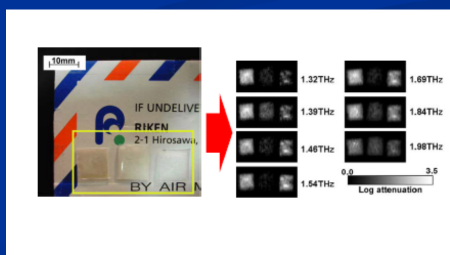


Image Kodo Kawase, RIKEN, Sendai

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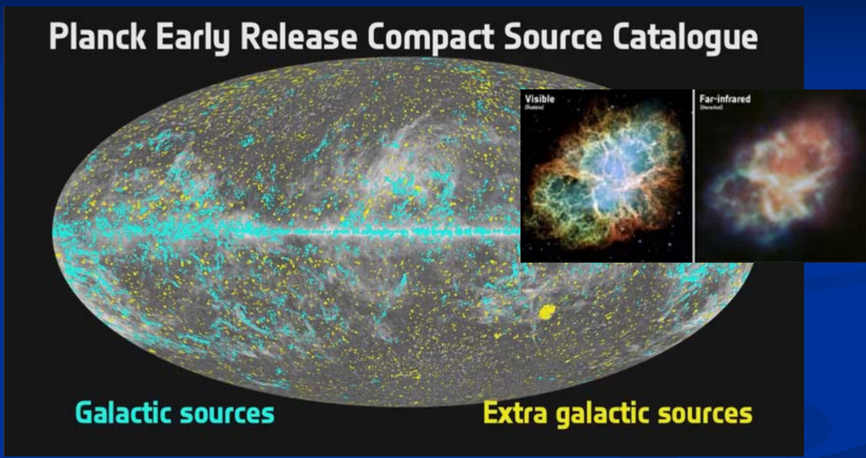
Why studying the THz domain? Astrophysics



The 15 000 objects in the "Early Release Compact Source Catalogue", where galactic objects – mainly compact dust clouds – are shown in green, and extragalactic objects – mainly radio galaxies and galaxies with a large thermal emission from dust – are shown in yellow. The larger yellow blob to the lower right is the Large Magellanic Cloud, a dwarf galaxy orbiting the Milky Way.

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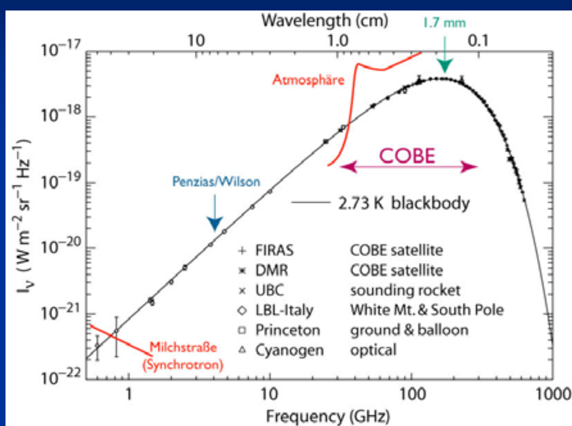
Why studying the THz domain? Astrophysics



Cosmic Microwave Background Radiation (CMB)

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Modern physics in the THz domain

- Techniques
- Interaction of THz EM waves with matter

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Sources : The Holy Grail !

- At the present time, no source exhibits simultaneously all the requested characteristics for actual applications:
  reliability, compactness, low power consumption, efficiency, brightness, tunability, room temperature operation …
- Different solutions and technologies are studied
- Strong competition between technologies and between laboratories

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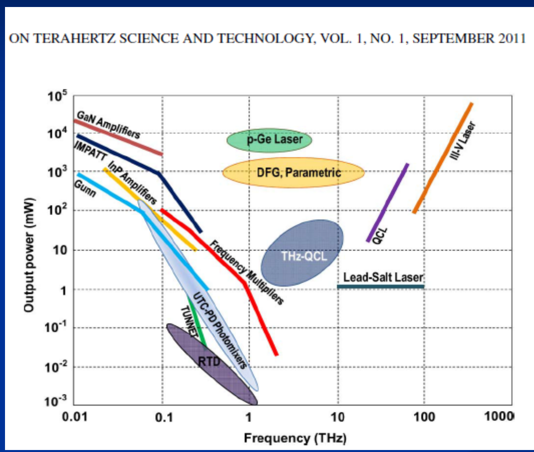
The problem : example of CW sources



Limited by: electrical transport RC, τ — optical transitions $h\nu/kT$

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Sources

- Blackbody sources
  - Mercury lamps, globar…
- Electronic tubes
  - Backward oscillators (BWO), klystrons…
- "Big" lasers and facilities
  - Free electron lasers, molecular lasers, synchrotrons…
- p:Ge lasers, nonlinear microwave lines…
- Quantum cascade lasers
- Electronic components: negative differential resistance
- Optoelectronic sources

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Optoelectronics sources

- Converting optical beams into THz beams
- Needed :
  - an optical source (laser)
  - a nonlinear device
- Pulsed and CW operations
- Advantages : using efficient laser sources and optical technologies

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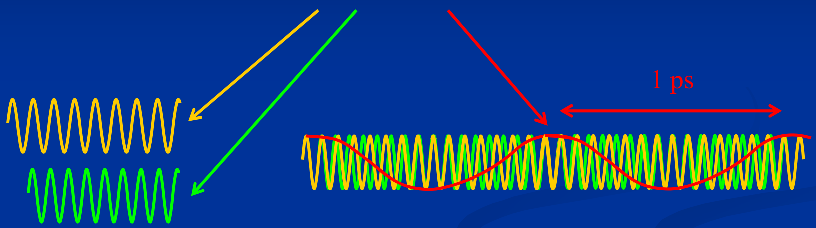
CW : optical beating

- Optical beating (ω_1-ω_2=Ω)



- f_{THz}~10^{12} Hz f_{laser1}~f_{laser2}~ 10^{15} Hz

  $\Delta f_{laser}/f_{laser}$~$10^{-3}$

  f_{THz} stable (Δf_{THz}~1 GHz), $\Delta f_{laser}/f_{laser}$~$10^{-6}$

Basic idea :
2 lasers with different colors + nonlinear device = THz signal

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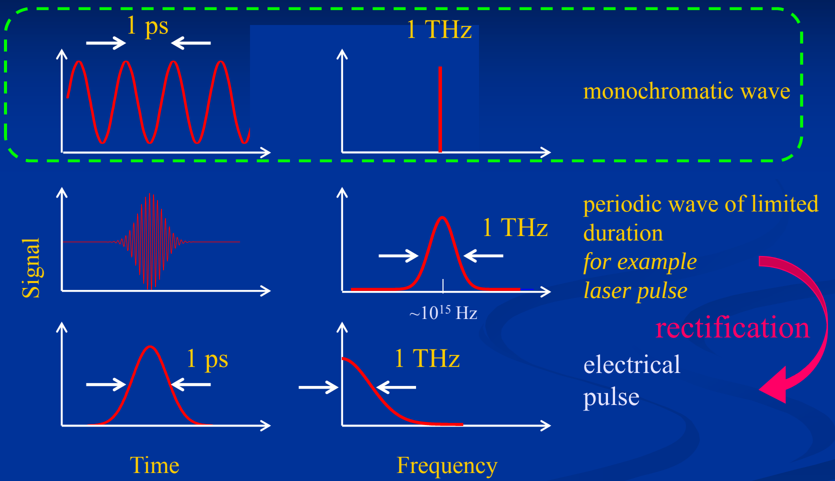
Time domain vs frequency domain



Basic idea:

sub-picosecond laser pulse + nonlinear device (rectification) = THz signal

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The nonlinear optoelectronic device

Basic idea:

laser (CW beating or pulsed) + nonlinear device = THz signal

- **Photoexcitation in SC**
  - **Photoconductive antennas**
  - **Ultrafast photodiodes (UTC)**
- **Optical rectification in crystals**
- **…**

In both CW and pulsed operations

- **Ultrashort response:**

  shorter than the THz period i.e. picosecond

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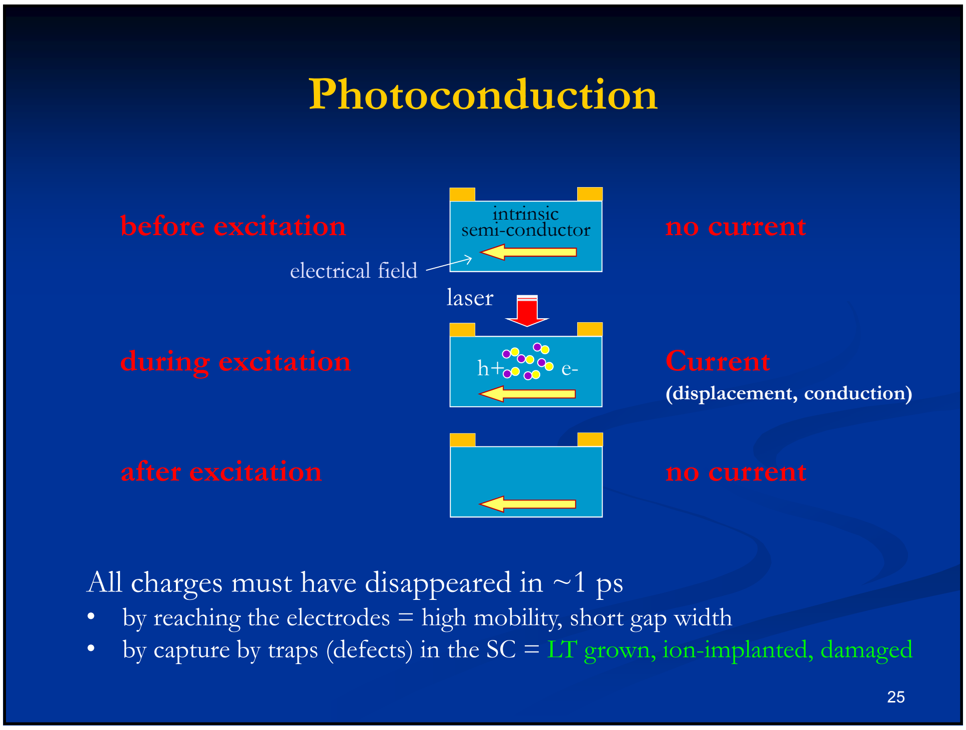
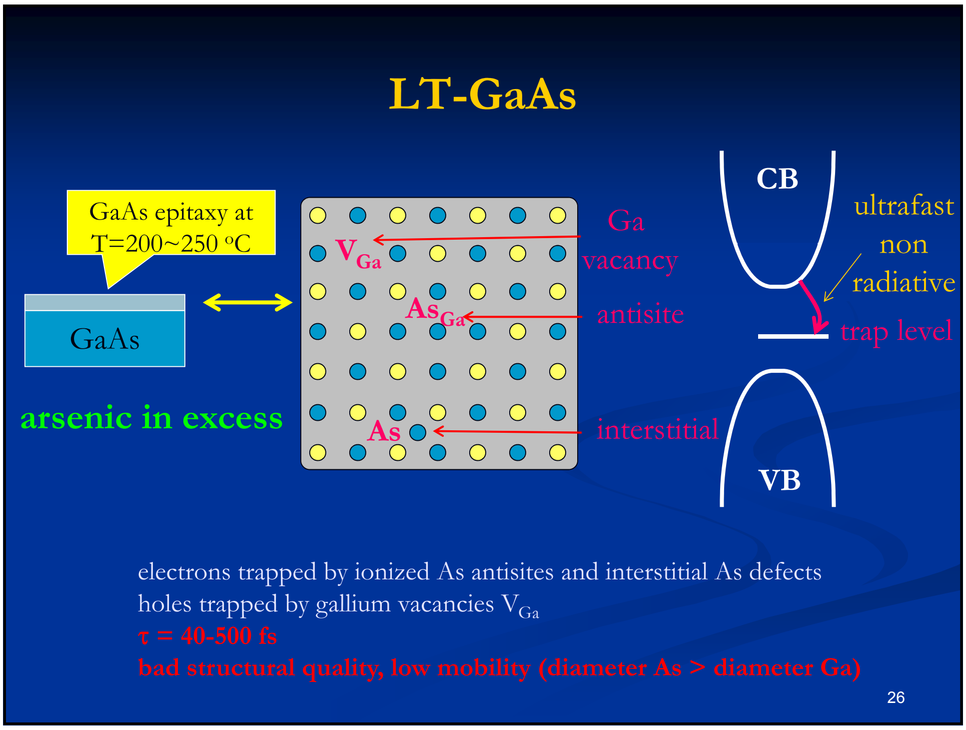
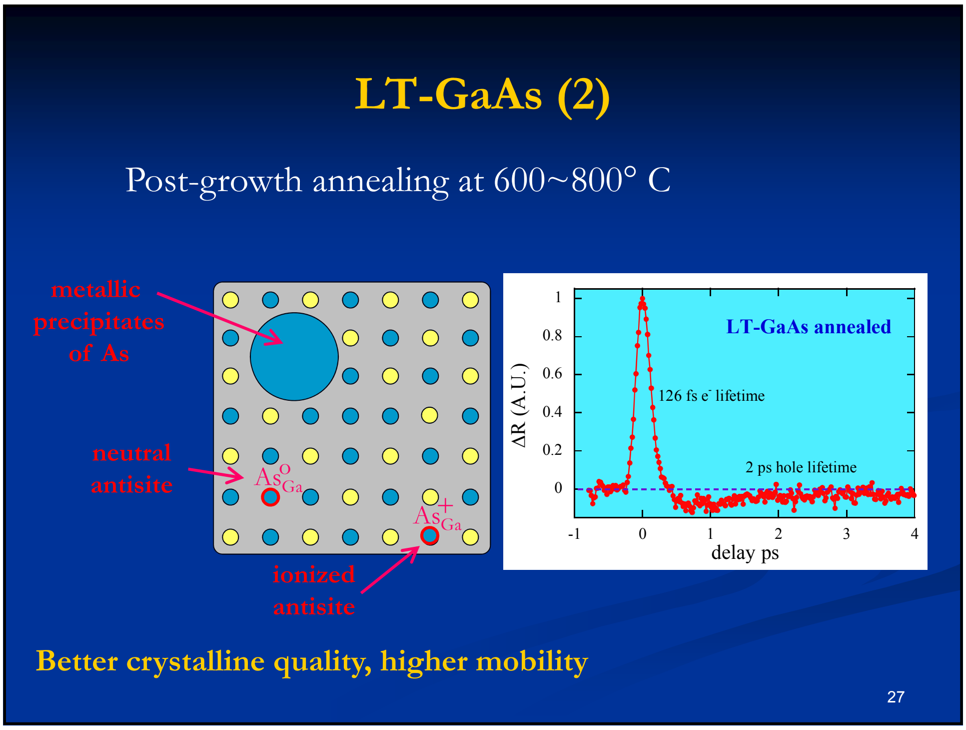
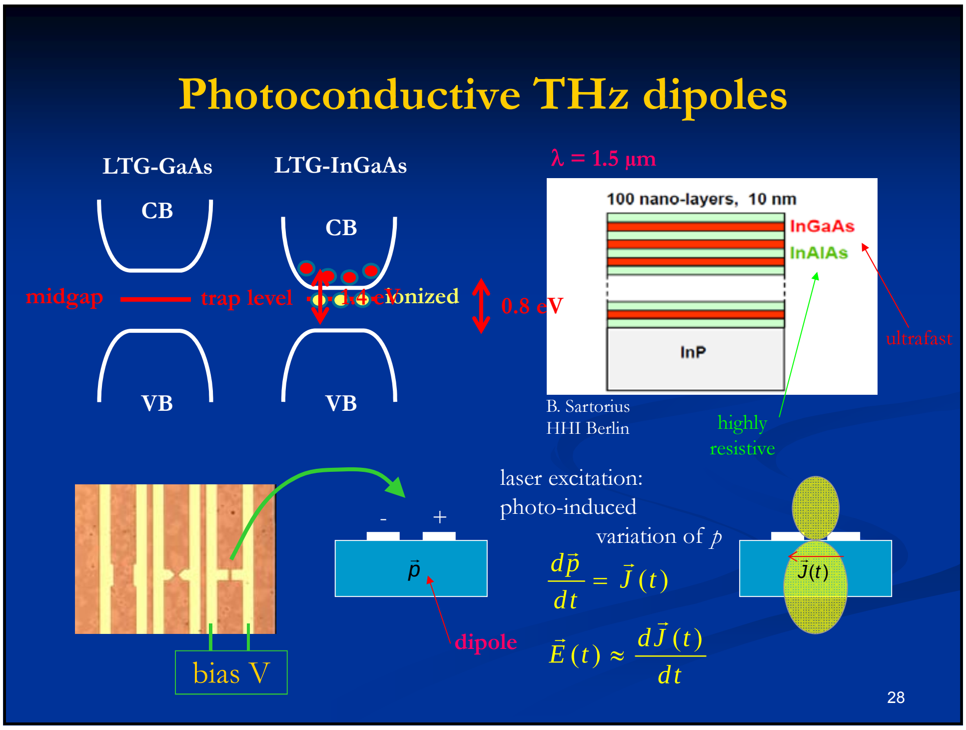

Photoconduction
before excitation
intrinsic semi-conductor
electrical field
no current
laser
during excitation
h+
e-
Current
(displacement, conduction)
after excitation
no current
All charges must have disappeared in ~1 ps
• by reaching the electrodes = high mobility, short gap width
• by capture by traps (defects) in the SC = LT grown, ion-implanted, damaged
25


LT-GaAs
GaAs epitaxy at T=200~250 °C
GaAs
arsenic in excess
V_Ga
As_Ga
As
Ga vacancy
antisite
interstitial
CB
VB
ultrafast non radiative
trap level
electrons trapped by ionized As antisites and interstitial As defects
holes trapped by gallium vacancies V_Ga
τ = 40-500 fs
bad structural quality, low mobility (diameter As > diameter Ga)
26


LT-GaAs (2)
Post-growth annealing at 600~800° C
metallic precipitates of As
neutral antisite
ionized antisite
LT-GaAs annealed
126 fs e- lifetime
2 ps hole lifetime
ΔR (A.U.)
delay ps
Better crystalline quality, higher mobility
27


Photoconductive THz dipoles
LTG-GaAs
LTG-InGaAs
CB
VB
midgap
trap level
ionized
0.8 eV
λ = 1.5 µm
100 nano-layers, 10 nm
InGaAs
InAlAs
InP
ultrafast
highly resistive
B. Sartorius HHI Berlin
bias V
dipole
laser excitation: photo-induced variation of p
$\frac{d\vec{p}}{dt} = \vec{J}(t)$
$\vec{E}(t) \approx \frac{d\vec{J}(t)}{dt}$
28

Nonlinear optical techniques

$$\vec{P} = \varepsilon_o\left(\chi_L \vec{E}_{laser} + \overleftrightarrow{\chi}^{(2)}_{NL} : \vec{E}_{laser} \cdot \vec{E}_{laser} + \overleftrightarrow{\chi}^{(3)}_{NL} : \vec{E}_{laser} \cdot \vec{E}_{laser} \cdot \vec{E}_{laser} \cdots\right)$$

$$\vec{E}_{laser} = \vec{E}_1 e^{j\omega_1 t} + \vec{E}_2 e^{j\omega_2 t}$$

$$\overleftrightarrow{\chi}^{(2)}_{NL} : \vec{E}_{laser} \cdot \vec{E}_{laser} \quad \rightarrow \quad \overleftrightarrow{\chi}^{(2)}_{NL} : \vec{E}_1 \cdot \vec{E}_2 e^{j(\omega_1 - \omega_2)t}$$

Advantages

- no charge transport
- almost instantaneous nonlinear polarization

Ultra wideband frequency spectrum

- no need for microwave-line structure

But, as a nonlinear optical process, it requires

- high optical pump power
- phase matching, i.e. same velocities of optical and THz waves
- efficient NL crystal transparent in both optical and THz domains

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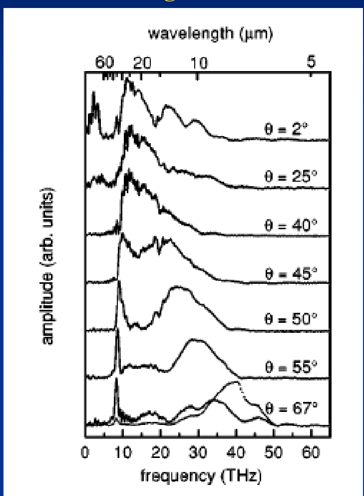
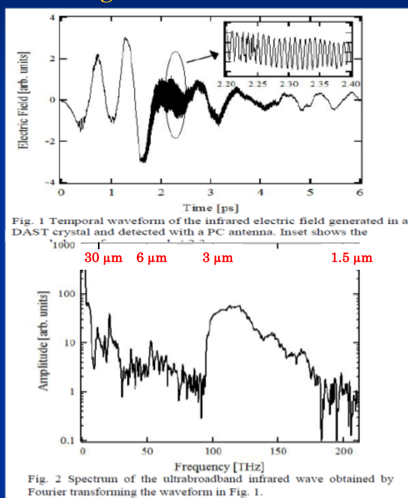
EO generation

Phase matching in GaSe



Huber *et al.*, APL 76, 3191 (2000)

EO THz generation in DAST



Eiichi Matsubara *et al.*, IRMMW 2010

30

Detectors

- Detectors of power-energy

  - slow** response: they integrate the signal

  *** as compared to the THz period*

- Detectors of field amplitude

  - ultrafast = sub-ps

  - no electronics is today able to read in real time the delivered signals ⟶ time-equivalent sampling techniques

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Basic definitions

- Sensitivity $S(\mathrm{V/W}) = \frac{V}{P}$
- Signal over noise ratio $SNR = \left(\frac{\bar{V}}{\sigma}\right)^2$
- Noise Equivalent Power $NEP =$ power $\Leftrightarrow SNR = 1$

  $NEP = \frac{V_{noise}}{S}$
- NEP in watt, but NEP of many detectors in the FIR

  $NEP \propto \sqrt{S \times \Delta f}$ $\quad S = sensitive\ area, \Delta f = bandwidth$
- Thus NEP measured for $\Delta f = 1$ Hz and given in W/Hz$^{1/2}$
- Noise equivalent differential temperature $NETD$ (passive imaging)

  variation of temperature at the scene which induces a variation of signal equal to the NEP

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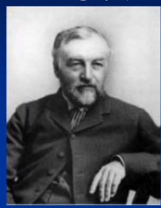
Bolometers

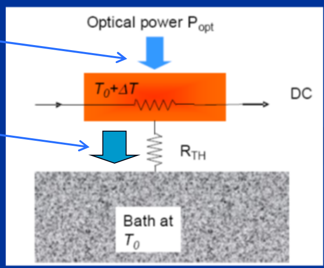
Samuel Langley (1880)



Absorption of EM waves
Increase of temperature
Thermometer (thermistor, supercond.,…)
Signal ↔ EM wave energy

Heat capacity C (J/K)

Thermal conductance g (W/K)



$$\frac{\Delta R}{R} \propto P_{THz}\frac{\alpha}{g}, \quad \alpha = \frac{1}{R}\frac{dR}{dT}$$

Sensitive bolometers:
α (thermal coefficient of the resistance) large: the best are superconductors.
g (thermal conductance) small: low T, vacuum, suspended membranes…

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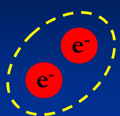
Superconducting bolometers



Cooper pair
R=0
E=3.5 $k_B T_C$ (BCS theory)
T_C normal-to-superconductor transition T

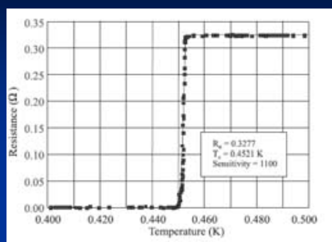
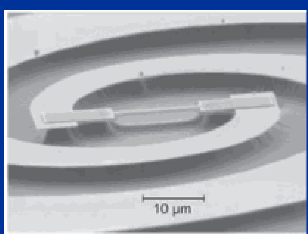
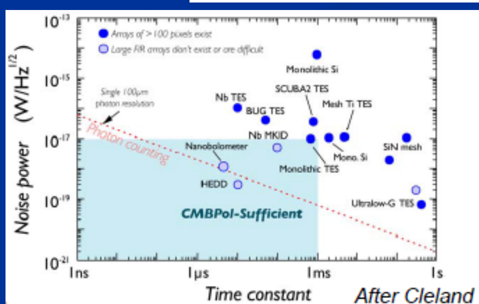


Fig. 23. Superconducting transition at 452 mK for a Mo/Au bilayer [150].

Hot electron bolometer (HEB):
Heating by direct illumination of the superconductor.





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Room temperature microbolometers

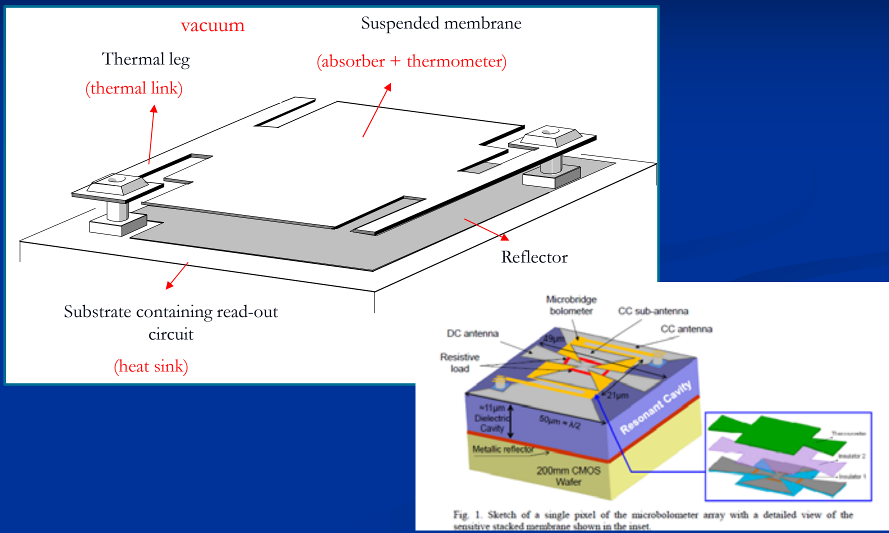
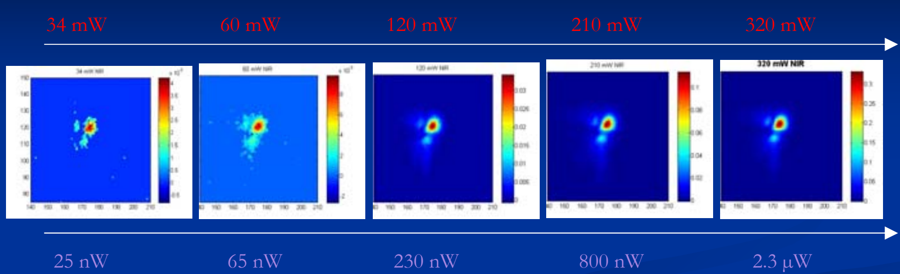
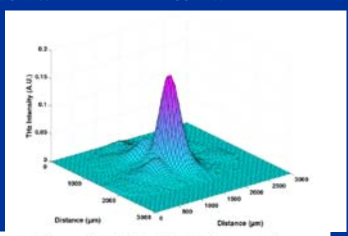


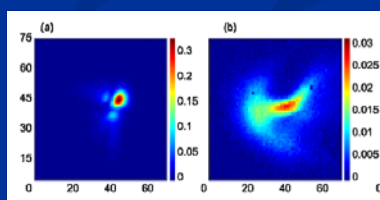
Fig. 1. Sketch of a single pixel of the microbolometer array with a detailed view of the sensitive stacked membrane shown in the inset.

D. T. Nguyen, PhD thesis, Grenoble 35

TDS system characterization with the LETI-CEA camera







Imaging of broadband terahertz beams using an array of antenna-coupled microbolometers operating at room temperature

Jonathan Oden, Jérôme Meilhan, Jérémy Lalanne-Dera, Jean-François Roux, Frédéric Garet, Jean-Louis Coutaz, and François Simoens

25 February 2013 / Vol. 21, No. 4 / OPTICS EXPRESS 4817

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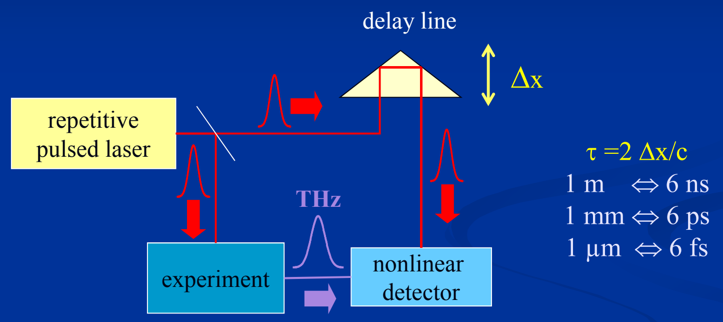
Optoelectronics sampling techniques

Repetitive signals (mode-locked fs lasers)
main advantage : the use of a slow detector



τ =2 Δx/c
1 m ⇔ 6 ns
1 mm ⇔ 6 ps
1 µm ⇔ 6 fs

$$S(\tau) \approx \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} S_{signal}(t'-\tau)\ S_{probe}(t)\ \eta_{nonlinearity}(t-t')\ dt\ dt'$$

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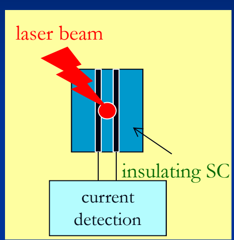
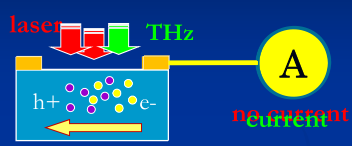
Detection by photoconduction





$$J(t) = N(t)\, q\, \mu\, E_{THz}(t) = \left(\int_{-\infty}^{+\infty} \eta\, I_{laser}(t-t')dt'\right) q\, \mu\, E_{THz}(t)$$

- field detector
- no signal (noise) between laser pulses

laser = triggering the receiver

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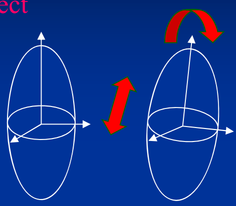
EO detection

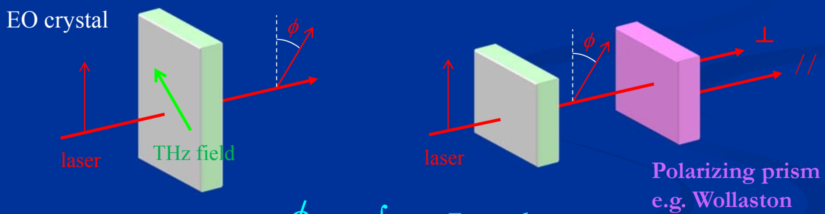
EO (Pockels) effect

$$\frac{x^2}{n_x^2}+\frac{y^2}{n_y^2}+\frac{z^2}{n_z^2}=1$$



THz field

$$x^2\left(\frac{1}{n_x^2}+r_{1j}E_j\right)+y^2\left(\frac{1}{n_y^2}+r_{2j}E_j\right)+z^2\left(\frac{1}{n_z^2}+r_{3j}E_j\right)+2r_{4j}E_jyz+2r_{5j}E_jxz+2r_{6j}E_jxy=1$$



$$\phi \cong \int_{thickness} r_{ij}\, E_{THz,j}\, dx$$

- field detector
- no signal (noise) between laser excitation

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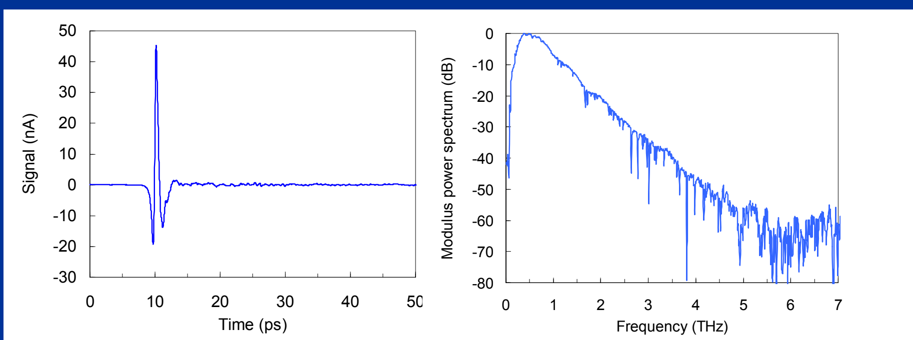
Typical THz signal radiated by a photoconducting switch



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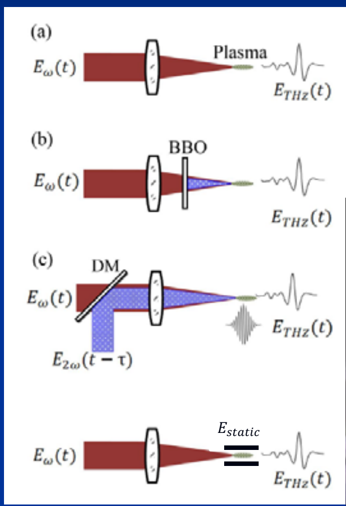
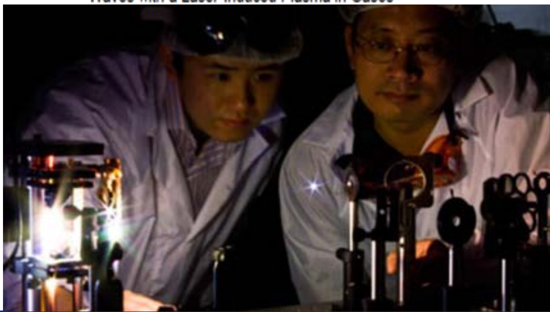
Generation in air/gas



1993	H. Hamster, *et al.* – Subpicosecond, electromagnetic pulses from intense laser-plasma interaction
2000	D.J. Cook, *et al.* – Intense terahertz pulses by four-wave rectification in air
2005	T. Bartel, *et al.* – Generation of single-cycle THz transients with high electric-field amplitudes
2006	X. Xie, et al. – Coherent Control of THz Wave Generation in Ambient Air; J. Dai, et al. – Detection of Broadband Terahertz Waves with a Laser-Induced Plasma in Gases



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Generation in air/gas: how?

Four-wave mixing
D. J. Cook, R. M. Hochstrasser, ***Opt. Lett. 25****, 1210 (2000)* $\omega_{THz} = \omega + \omega - 2\omega$
too weak effect

Asymmetric transient current of ionized electrons
M. Kress, et al., ***Opt. Lett. 29****, 1120 (2004)*

Nonlinear optics in the strong field regime
(≠ Bloembergen's perturbation theory)
N. Karpowicz and X.-C. Zhang, ***Phys. Rev. Lett. 102,*** *093001 (2009)*

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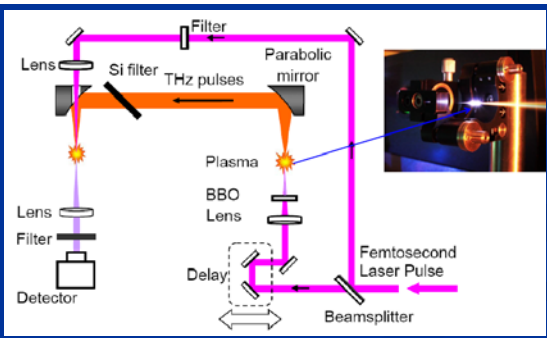
Detection in air/gas

Four wave mixing (generation)

$$E_{THz}(t) \propto \chi^{(3)} E_{2\omega}(t)\, E^*_{\omega}(t)\, E^*_{\omega}(t) \cos(\phi)$$

THz induced SHG (Air Breakdown Coherent Detection ABCD)

$$E_{2\omega}(t) \propto \chi^{(3)'} E_{THz}(t)\, E^*_{\omega}(t)\, E^*_{\omega}(t) \cos(\phi')$$



Jianming Dai and X.-C. Zhang , *The Institute of Optics, University of Rochester*

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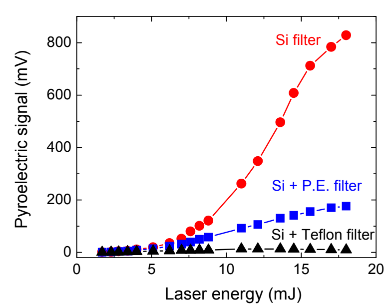
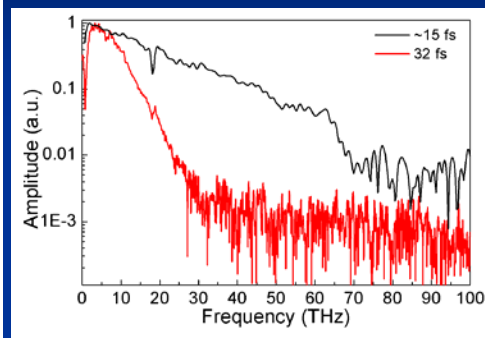
Generation in air/gas



• THz energy ~ 5 μJ/pulse with Kr

K. Y. Kim *et al.*, Nature Photonics doi:2008.153 (2008).



From X.-C. Zhang, Rochester

5 μJ · 50 fs pulse = peak power 100 GW D = P/S = 10^{15} W/cm

typ. D = 10^{12}~10^{13} W/cm ^{2}

D = P/S = $E^2/2Z_o$ E = $(2Z_oP/S)^{1/2}$ = 800 MV/cm typ. E ~ 10 MV/cm

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Nonlinear THz optics

Applications of Strong THz fields

THz pump experiments
- THz pumping of metals, insulators, and correlated electron materials.
- Coherent band-gap distortion & phase transition.
- THz-pump optical-probe experiments.
- THz coherent control

Rapid THz imaging
- Biomedical and security imaging

Strong THz sources

E_{THz} > 1 MV/cm

Nonlinear THz Optics
- THz 2nd, 3rd nonlinear effects.
- Extreme nonlinearity with ponderomotive energy > photon energy
- THz-optical nonlinear mixing

High magnetic field effects
- 1 MV/cm → 0.3 T
- Pulsed electron spin resonance
- THz spintronics

$$B = \frac{E}{c} = \frac{1\,\mathrm{MV/cm}}{\mathrm{c}} = \frac{10^8}{3\times10^8} = 0.3\ \mathrm{T}$$

* M. S. Sherwin *et al.*, *DOE-NSF-NIH Workshop on Opportunities in THz Science*

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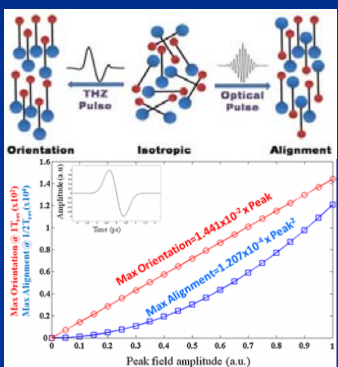
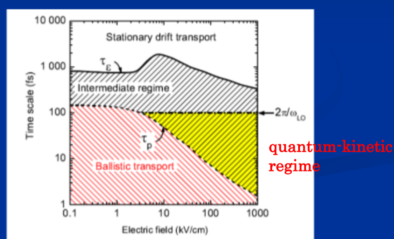
Nonlinear THz optics (2)

Orientation of gas phase molecules by THz fields, Keith Nelson's team, MIT



Molecular orientation and alignment by single-cycle THz pulses, S. Fleischer, Y. Zhou, R.W. Field, and K.A. Nelson, *Phys. Rev. Lett.* **107**, 163603 (2011).

Quantum-kinetic regime of conduction in GaAs, Thomas Elsaesser, Berlin



Coherent ballistic motion of electrons in a periodic potential
W. Kuehn, P. Gaal, K. Reimann, M. Woerner, T. Elsaesser und R. Hey, PRL 104, 146602-1–4 (2010)

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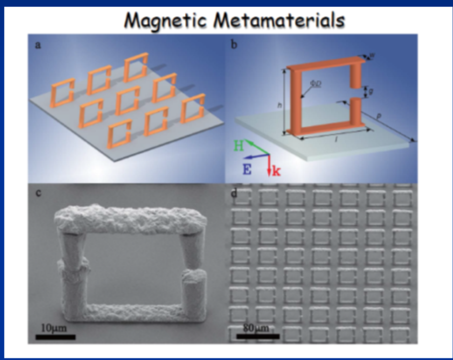
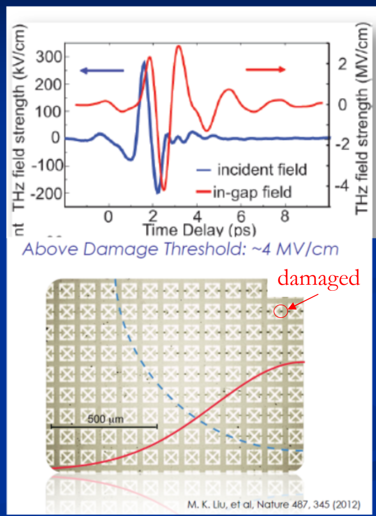
Nonlinear THz optics (3)

THz metamaterials, Rick Averitt, UCLA





Tesla magnetic field without superconducting coil cryogenic magnet

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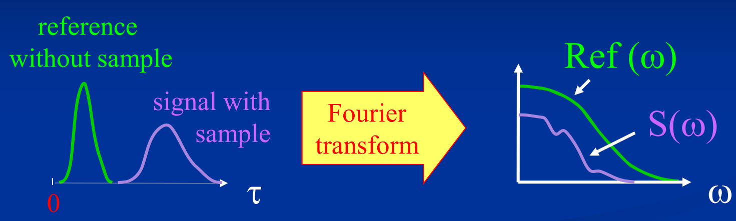
THz time-domain spectroscopy



T(ω)=S(ω)/Ref(ω)

2 inputs: τ=0, S(τ) → S(ω) complex
→ T(ω) complex → n(ω), α(ω)

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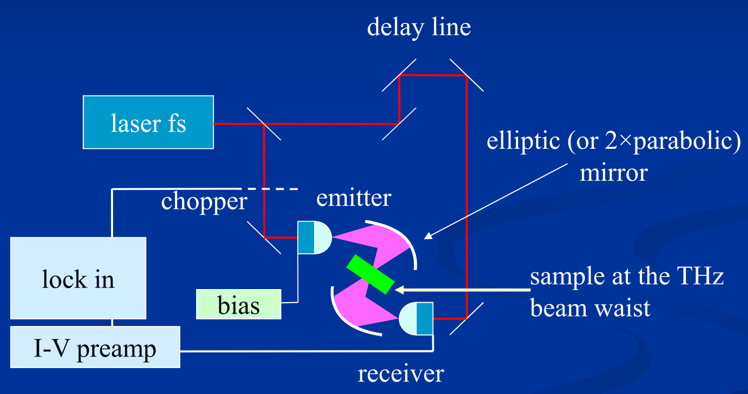
THz TDS : experimental set up



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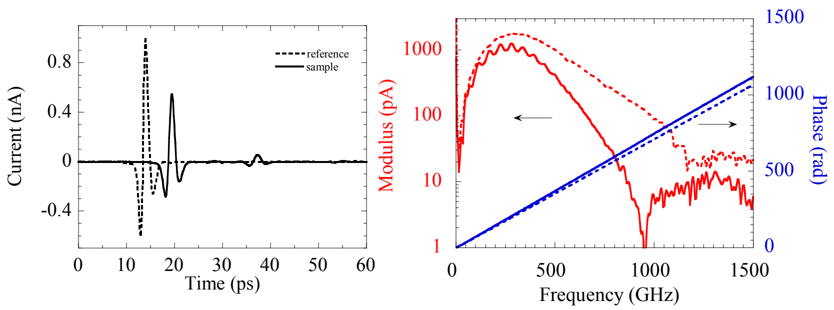
Temporal signals with samples

Schott BK7 glass, 1.065 mm thick



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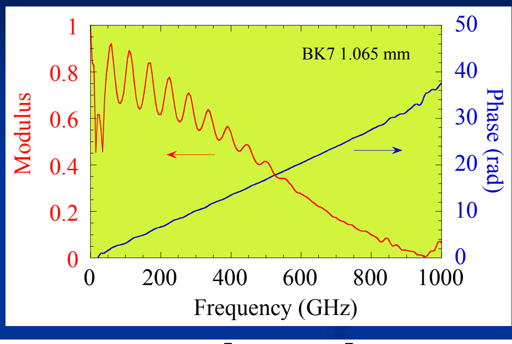
Transmission coefficient



$$T(\omega)=\frac{4\,\tilde{n}}{(1+\tilde{n})^2}\times\frac{\exp\left[-i(\tilde{n}-1)\frac{\omega d}{c}\right]}{1-\left(\frac{\tilde{n}-1}{\tilde{n}+1}\right)^2\exp\left[-2i\,\tilde{n}\frac{\omega d}{c}\right]}\qquad \tilde{n}=n-i\kappa$$

Inverse electromagnetic problem

See for example L. Duvillaret, F. Garet and J.-L. Coutaz, *IEEE JSTQE* **2**, 739-746 (1996)

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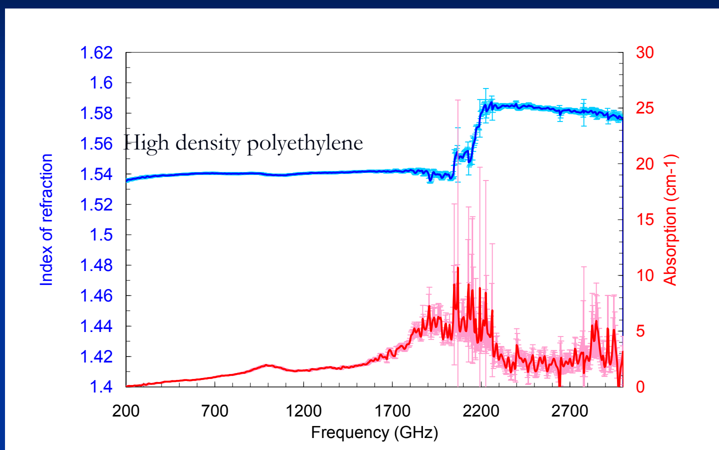
Example : HDPE



frequency resolution **$\Delta f = 1/\Delta T_{record} \sim$ 3-10 GHz**

$\Delta n/n \sim 0.1\ \%$ $\Delta\alpha \sim 0.1\ cm^{-1}$ $\Delta L/L \sim 1\ \%$

L. Duvillaret et al., Applied Optics 38, 409 (1999)

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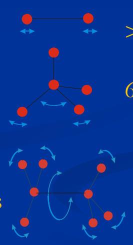
Interaction of THz with matter

Energy ~ meV

Vibrations of

Bonds		>21 THz
Bond angles		6-27 THz
Torsion angles		< 9 THz

→ excitation of:

- molecular rotations
  - especially polar molecules (water)
- Phonons (crystals)
- Localized vibrations (amorphous)
- Free carriers (metal, doped SC)
- Cooper pairs in superconductors
- Intraband energy levels in quantum wells

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Vibration of molecules

- Simple di-atomic molecule

$$E = \left(n+\frac{1}{2}\right)h\nu_o - \left(n+\frac{1}{2}\right)^2 h\nu_o + B\,J\,(J+1) - D\,J^2\,(J+1)^2$$

electronic levels — anharmonicity — rotation — centrifugal force

$\Delta E_{J\rightarrow J+1} = h\,\nu_{J\rightarrow J+1} \approx 4B$ Spectrum = periodic comb

- Actual molecules
  - more complicated model
  - modes of vibration-rotation
    - – stretching modes (inter atomic distance)
    - – angular modes

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Vibration of molecules (2)

- Ex: H_2S_2

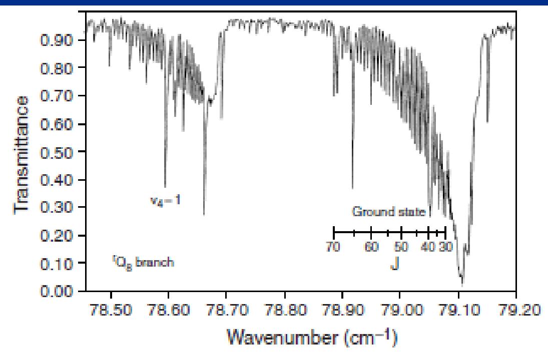
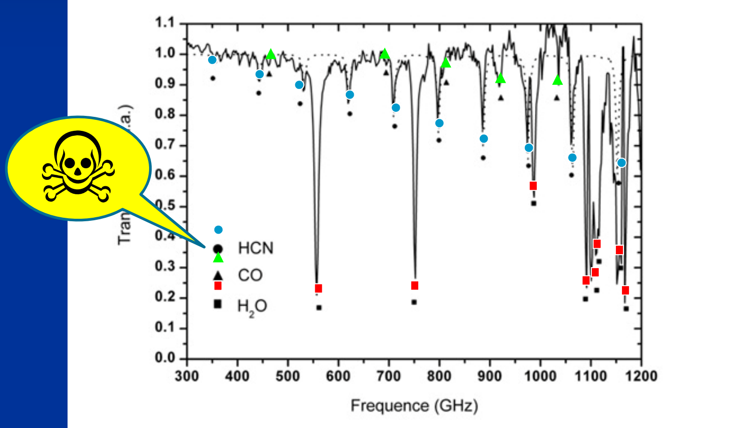


Figure 10 Far-infrared spectrum of H_2S_2 over a wavenumber range of 0.75 cm^{-1} measured at a resolution of 0.0025 cm^{-1}.

Instrumentation for Far-infrared Spectroscopy
Peter R. Griffiths[1] and Christopher Homes[2]

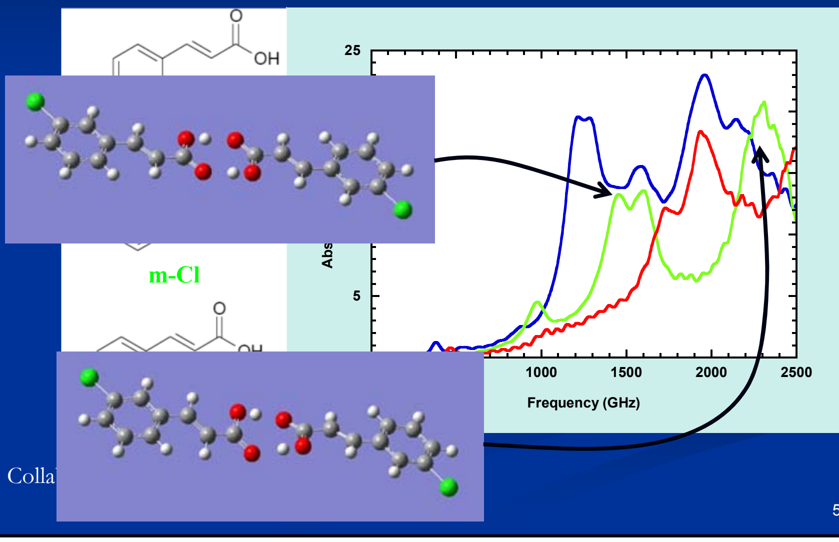
Vibration of molecules: applicartions

- remote chemical analysis
- example : cigarette smoke (courtesy R. Bocquet, Dunkerque, F)



Vibration of bigger molecules

- Chlorocinnamic acid structural isomer



Colla

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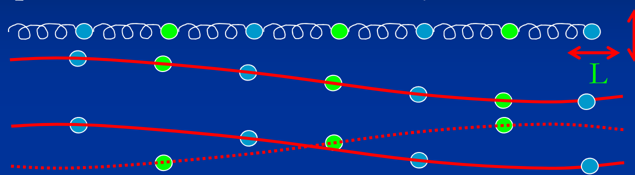
Phonons

- quantified vibration of the crystalline structure



$$\omega^2 = C\left[\frac{1}{M} \pm \sqrt{\frac{1}{M^2} - 4\frac{\sin^2(ka)}{m_1 m_2}}\right]$$

$k_{photon} \sim 0$ (photon = massless)
$k_{atom} \neq 0$ (atom = heavy)

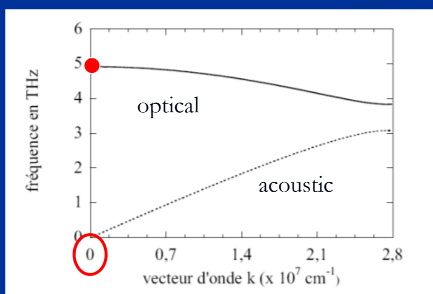


FIG. 2.12 – Courbe théorique de dispersion des phonons pour NaCl.

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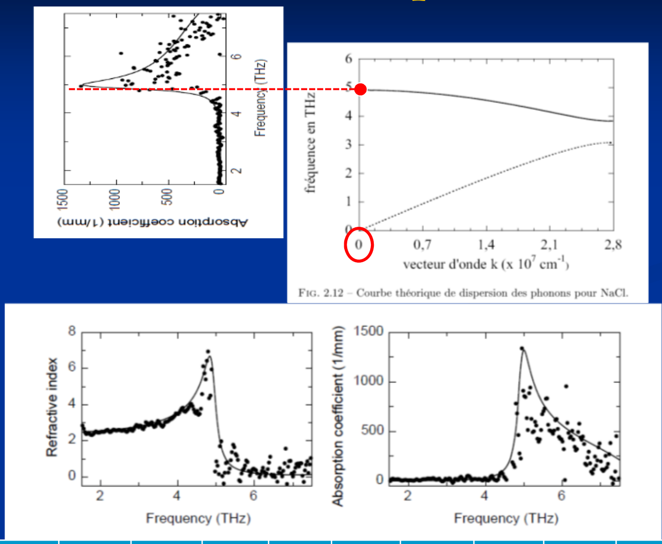
Phonons : example NaCl



Cristal	DAST	CdTe	NaCl	InSb	ZnTe	GaSe	ZnSe	GaAs	InP	ZnO
f_{phonon}(THz)	1.13	4.20	4.92	5.21	5.31	6.33	6.45	8.00	9.12	12.41

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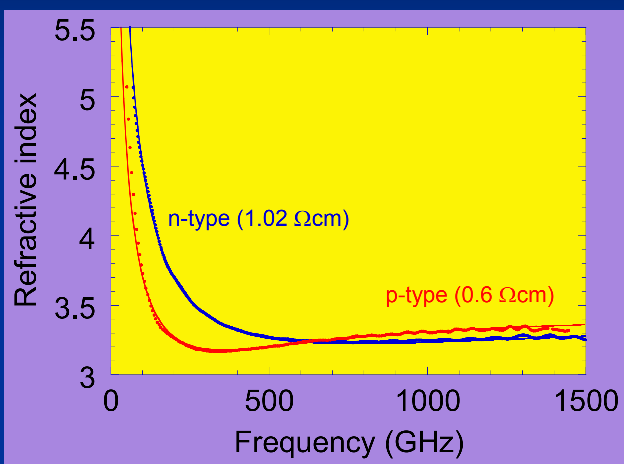
Free carriers : Drude model

Metal, doped SC: example of doped Si



J.-L. Coutaz et al., SPIE Proceedings **3795**, 457 (1999)

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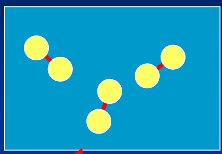
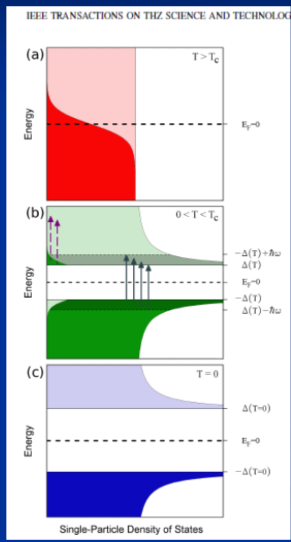
Superconductors





Cooper pairs = bosons
Phonon-assisted binding

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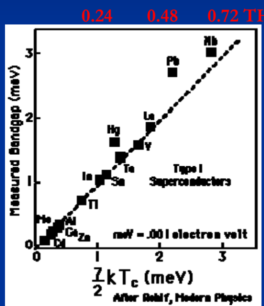
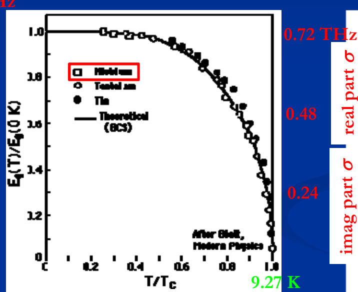
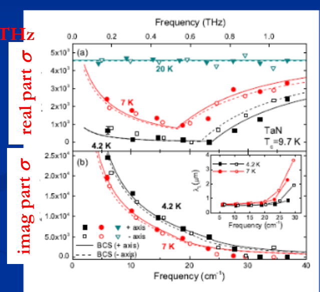
Superconductors

$E_{pairing}$=3.5 kT_c (Bardeen Cooper Schrieffer)
Energy to break a Cooper pair = E_{gap}(T) E_{gap}(T=0)=$E_{pairing}$







Uwe S. Pracht et al., IEEE Terahertz 2013

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Conclusion

I hope I was able to convince you that:

- Physics, Optics and Electronics with THz electro-magnetic waves are very interesting research topics.
  even if I was not able to present here all the aspects of THz science and technology
- Applications are numerous and will be certainly fruitful even for today life.

- There are still many unresolved questions to be solved and technology improvements to be performed.

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