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Advanced Imaging and Plasma Diagnostics
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December 5, 16:40 – 17:10, Oral Session Plasma (Imaging Technology) I3-2

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Spectoscopy and Imaging by Laser Excited Terahetz Waves

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Outline

1. Introduction
2. THz radiation by femtosecond laser excitation
3. THz time domain spectroscopy (THz-TDS)
4. THz imaging
5. Summary

1. Introduction

What is Terahertz (THz) Wave ?

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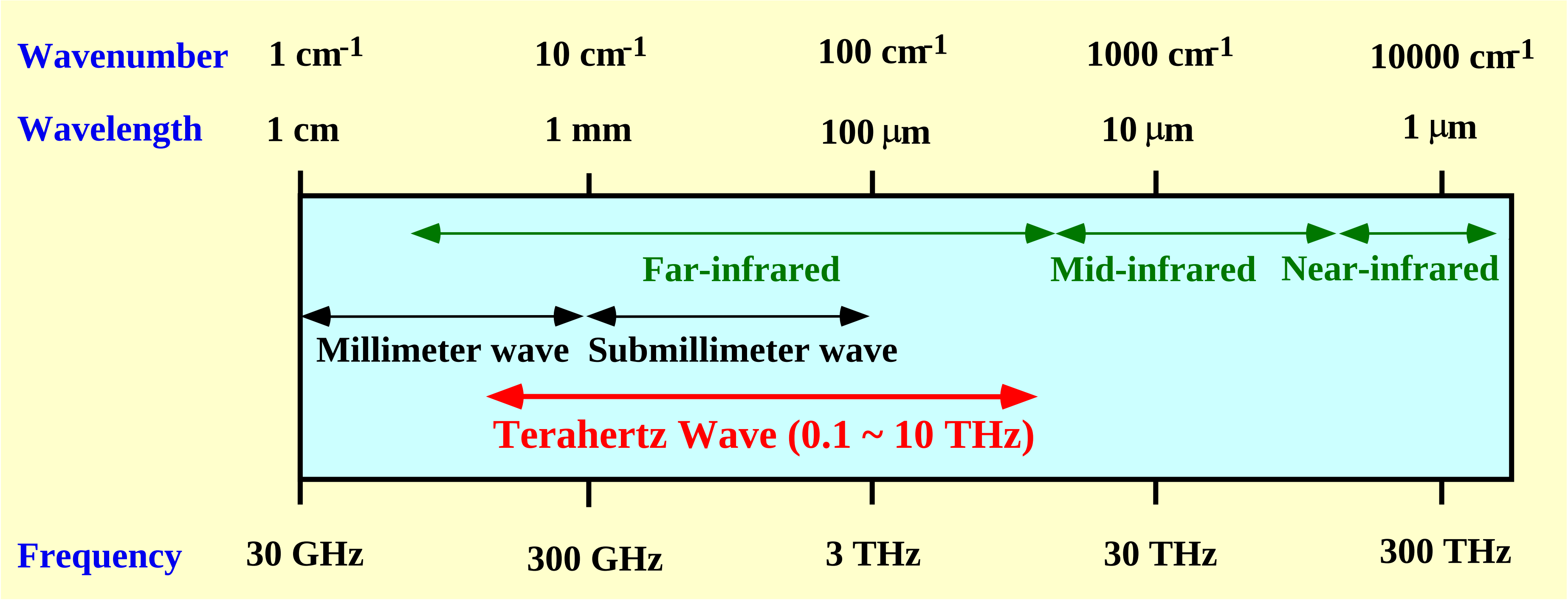
THz wave

Electromagnetic waves between microwave and visible light

$$1\ \mathrm{THz} = 10^{12}\ \mathrm{Hz}$$



Unexploited region of electromagnetic waves until very recently

Various Excitations in THz Region

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Material	Excitation
Semiconductor	Free carrier, Phonon, Plasmon, LO phonon-plasmon coupled mode, Cyclotron resonance, Magnetoplasma
Ferroelectrics	Soft mode
Superconductor	Superconducting energy gap, Quasiparticle excitation, Intrinsic Josephson plasma, 2D-super carrier plasmon-polariton
Photonic crystal	Photonic band
Liquid	Relaxation mode
Gas	Rotational mode, Plasma
Biomolecule	Vibrational mode, Collective excitation related to biological function

Terahertz Technology and Its Applications

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THz Technology

Radiation

Detection

Optical components

Spectroscopic systems

Imaging systems

Condensed Matter Physics & Chemistry

- Semiconductors
- Superconductors
- Polymers
- Photonic crystals
- Metamaterials
- Liquids

Biology & Medical Science

- Amino acids
- Peptides
- Proteins
- Biological tissues

Gas

- Molecular gases
- Gas plasmas

Security

- Mail bombs
- Illicit drugs
- Inflammable liquids

Industry

- Pharmaceutical process
- Semiconductor circuit diagnosis

2. THz radiation by femtosecond laser excitation

THz Radiation from Various Materials and Devices

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Excited by ultrashort laser pulses

1. Semiconductor photoconductive antennas (Auston switch)
2. Photoconduction at bulk semiconductor surfaces
3. Nonlinear optical effect in dielectrics and semiconductors
4. Ultrafast supercurrent modulation in high-T_c superconductors
5. Photo-ionization of gases under high electric fields
6. Various processes in ultraintense-laser-excited gas plasmas

THz Radiation from Photoconductive Antenna

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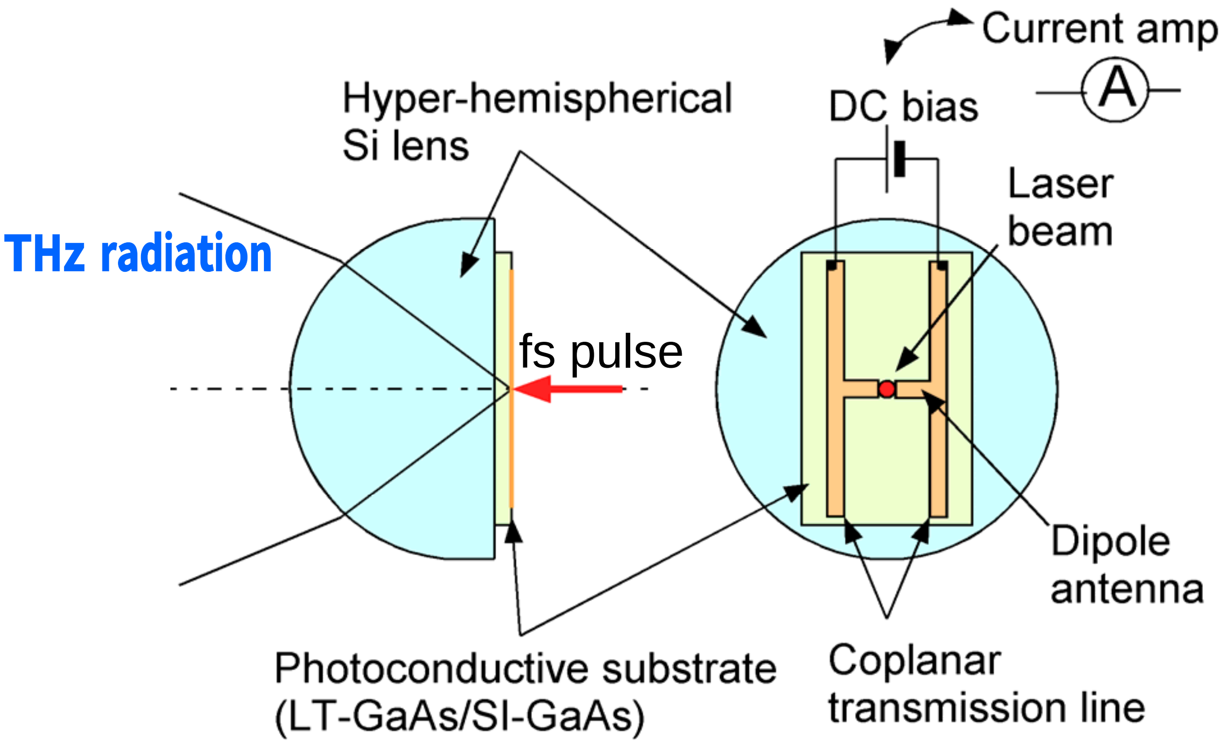
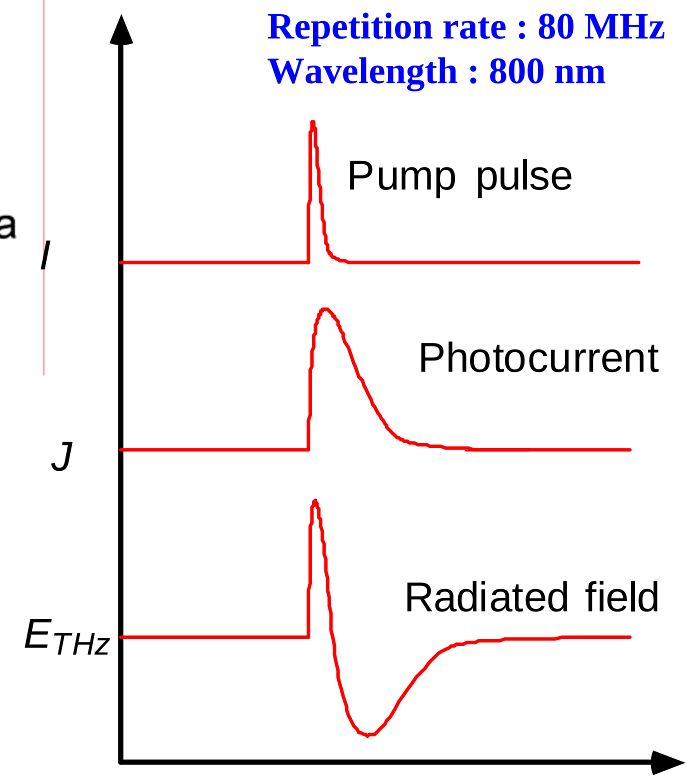
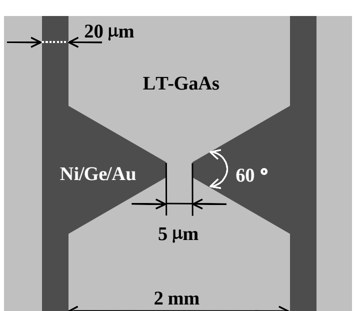


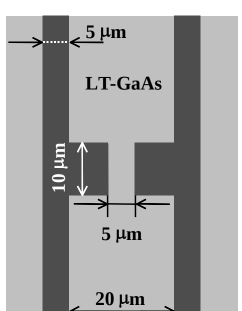
Photoconductive antenna
Photoconductive switch
Auston switch

Time width : 50 fs
Repetition rate : 80 MHz
Wavelength : 800 nm





bowtie



dipole

$$E_{THz}(t) \propto \frac{dJ(t)}{dt}$$

Emission and Detection of THz Waves

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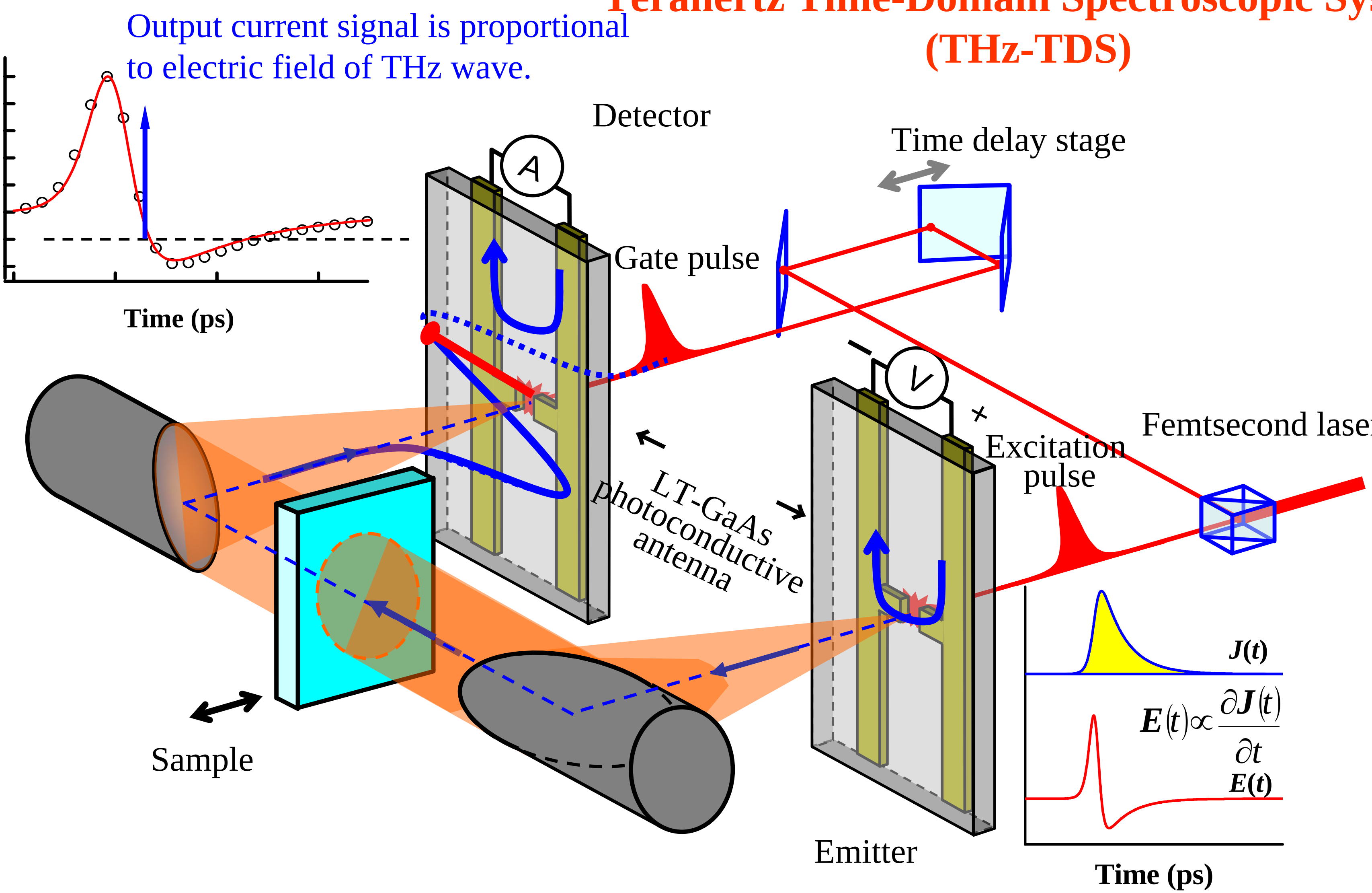
Terahertz Time-Domain Spectroscopic System (THz-TDS)



Developed as a spectroscopic system mainly by Grischkowsky’s group (IBM)

Wave Form and Spectrum of THz Radiation

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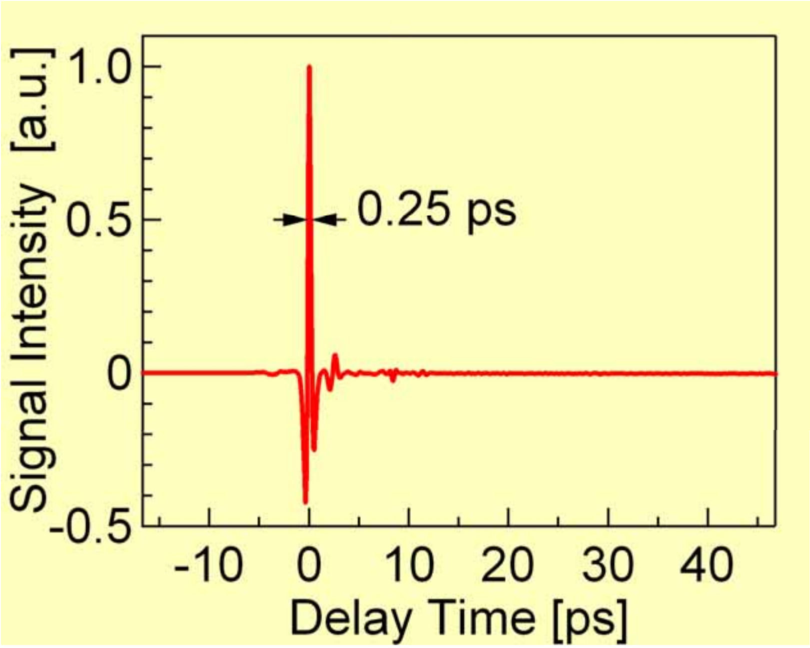
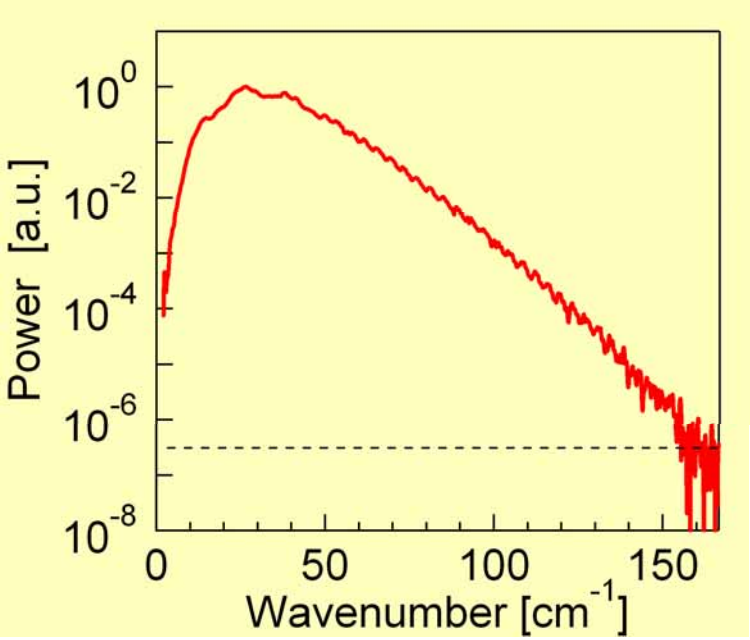
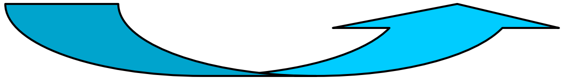
Photoconductive antenna：50μm dipole type
Laser pulse width：80fs







Fourier Transformation

100 cm^{-1} = 3 THz

Broadband radiation from nearly 0 to 5 THz

Principle of THz Radiation from Superconductor

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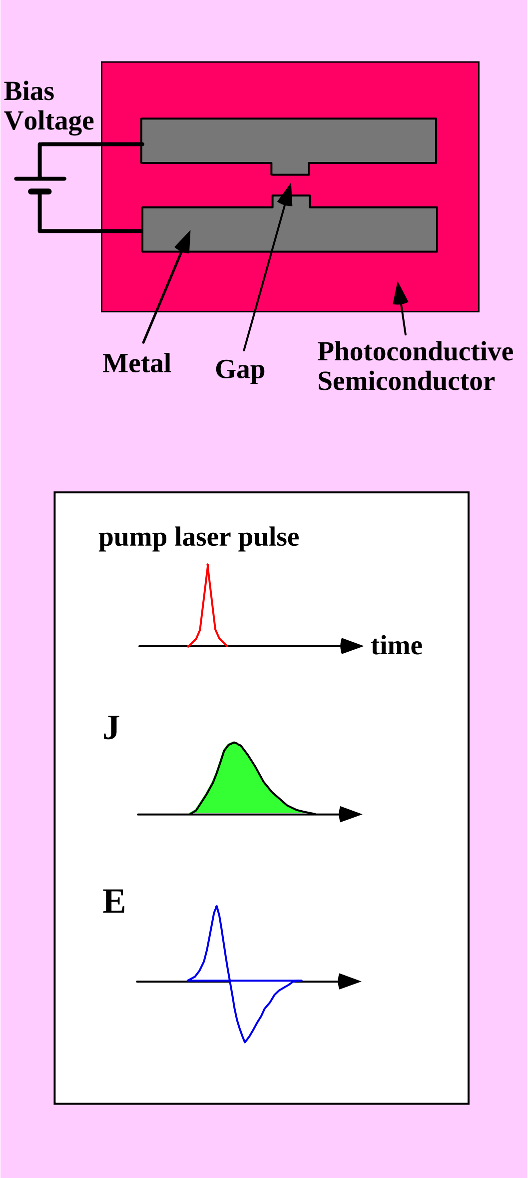
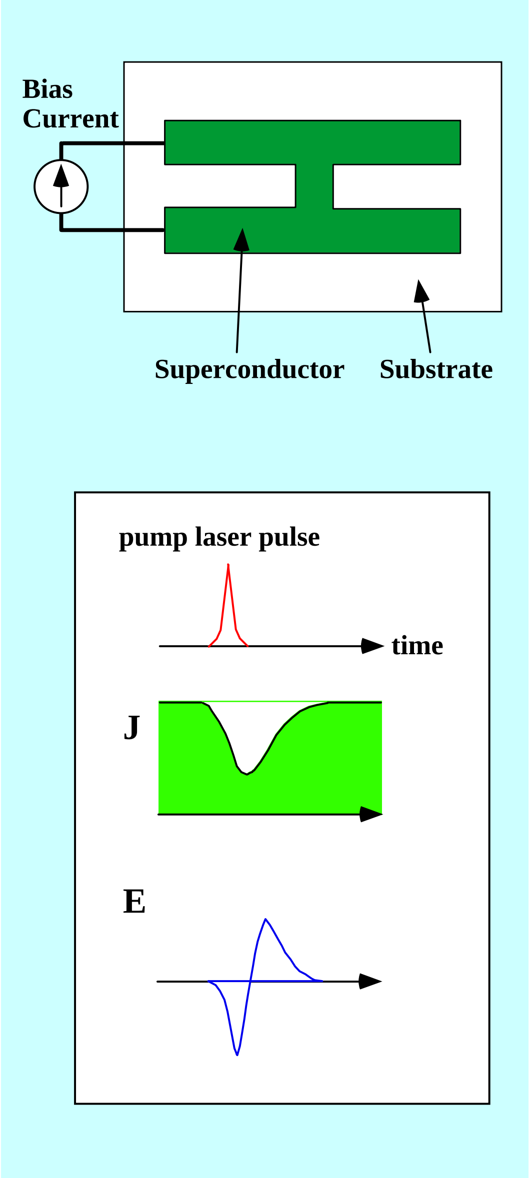
Semiconductor



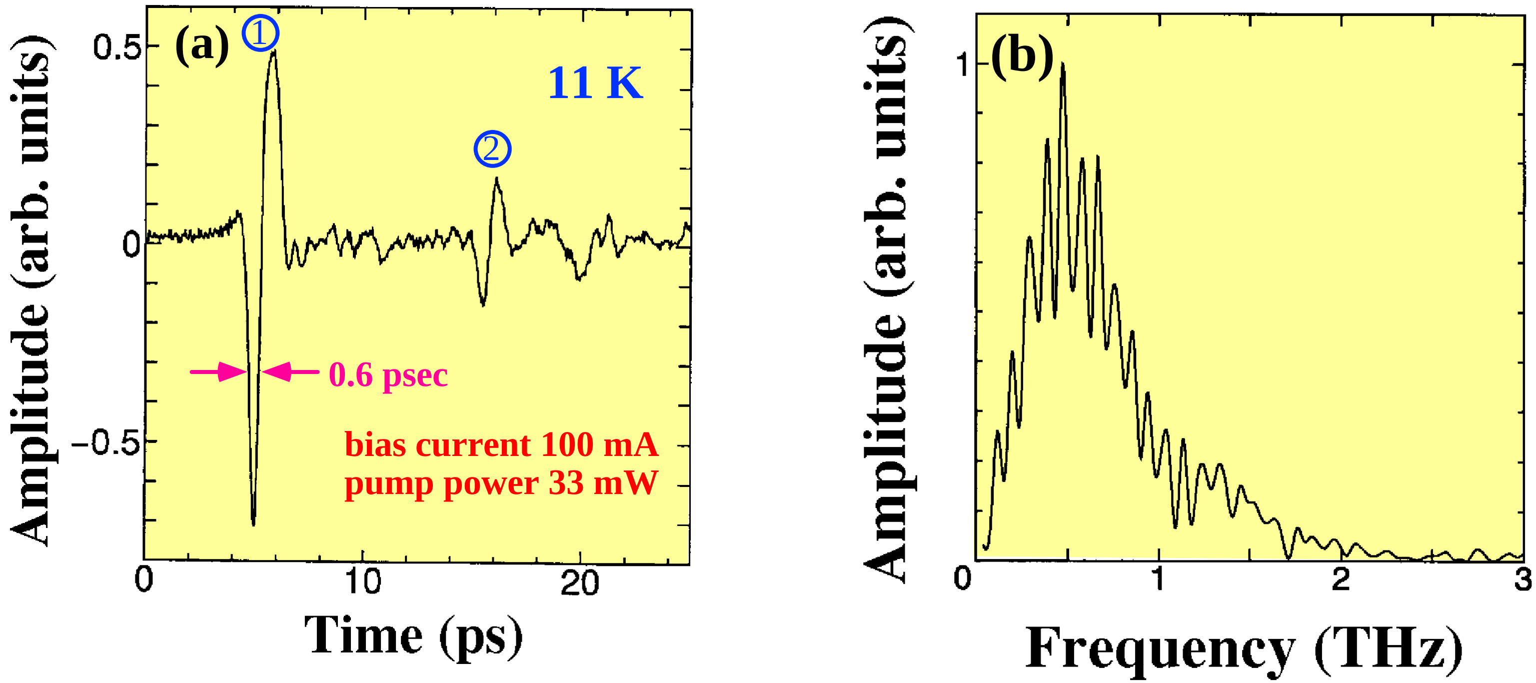
Superconductor

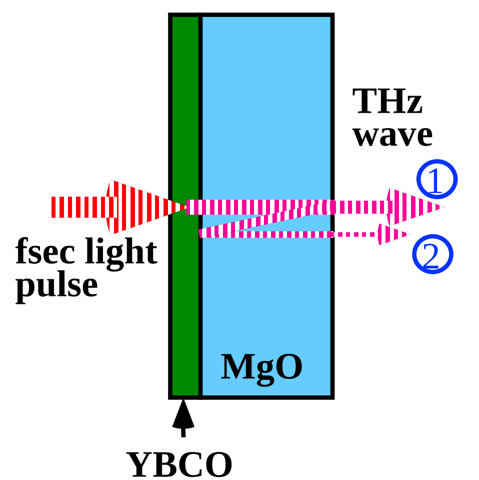


Ultrafast optical modulation of supercurrent

$$\mathbf{E} \sim d\mathbf{J}/dt$$

THz Radiation from High-T_c Superconductor





3. THz time domain spectroscopy (THz-TDS)

Principle of THz-TDS

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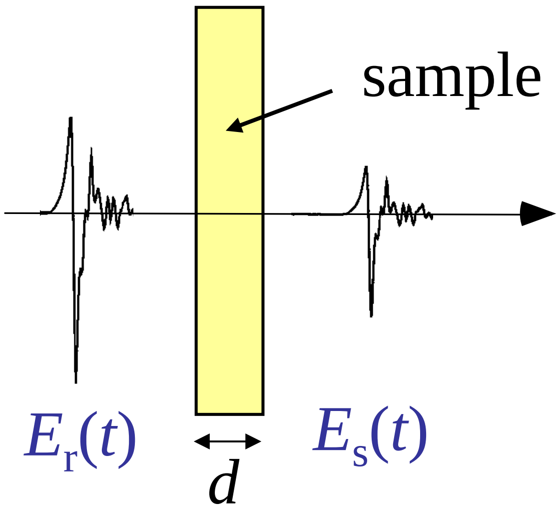
$$\tilde{n} = n - i\kappa$$



$E_r(t)$ $E_s(t)$

Complex Fourier transformation

$\tilde{E}_r(\omega)$ $\tilde{E}_s(\omega)$

$$\sqrt{T(\omega)}\exp(-i\phi(\omega)) = \frac{\tilde{E}_s(\omega)}{\tilde{E}_r(\omega)}$$

Transmittance — Phase shift

$$= \tilde{t}_{as}(\omega)\tilde{t}_{sa}(\omega)\exp\left\{i\frac{(\tilde{n}(\omega)-1)d\omega}{c}\right\}\sum_{l=0}^{m}\left\{(r_{sa}(\omega))^2\exp\left(i\frac{2\tilde{n}(\omega)d\omega}{c}\right)\right\}^l$$

Derivation of physical quantities

$$\tilde{n}(\omega)^2 = \tilde{\varepsilon}(\omega) = \varepsilon_{Si} - i\tilde{\sigma}(\omega)/\omega\varepsilon_0$$

Various Types of THz-TDS System

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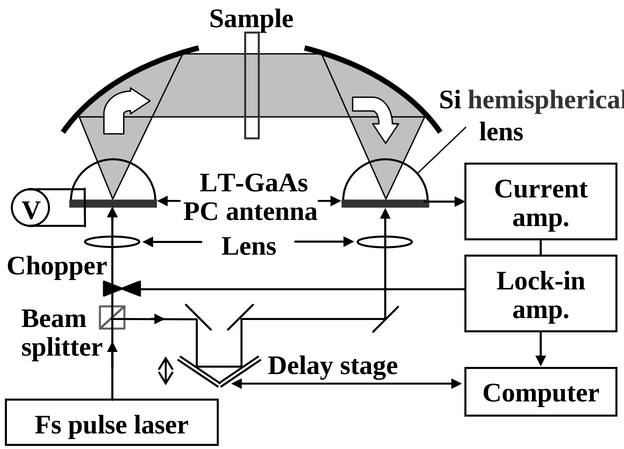
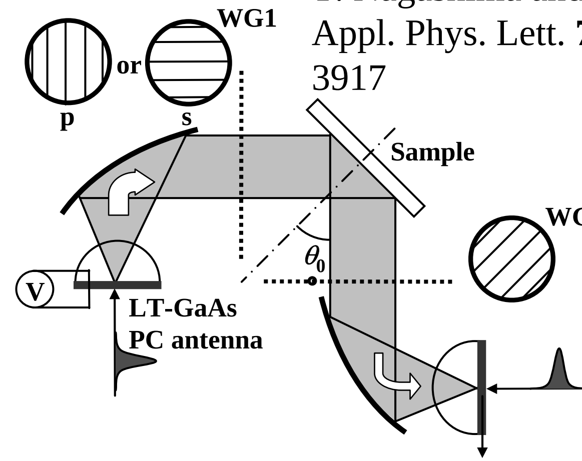
Transmission type



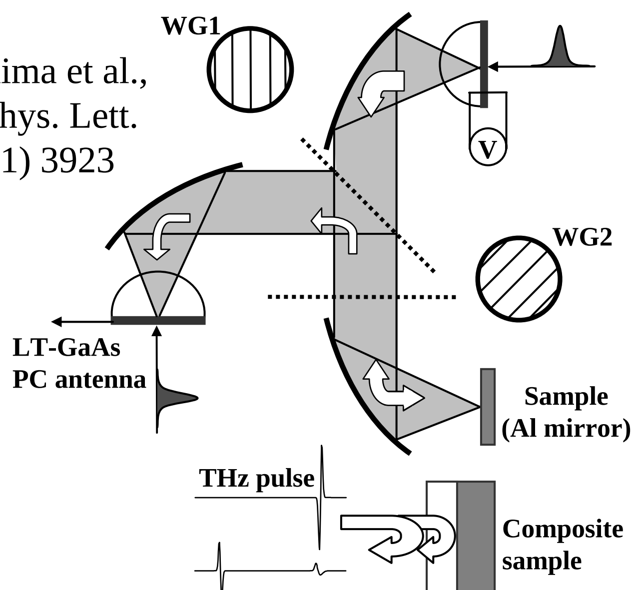
Ellipsometry type

T. Nagashima and M. Hangyo, Appl. Phys. Lett. **79** (2001) 3917

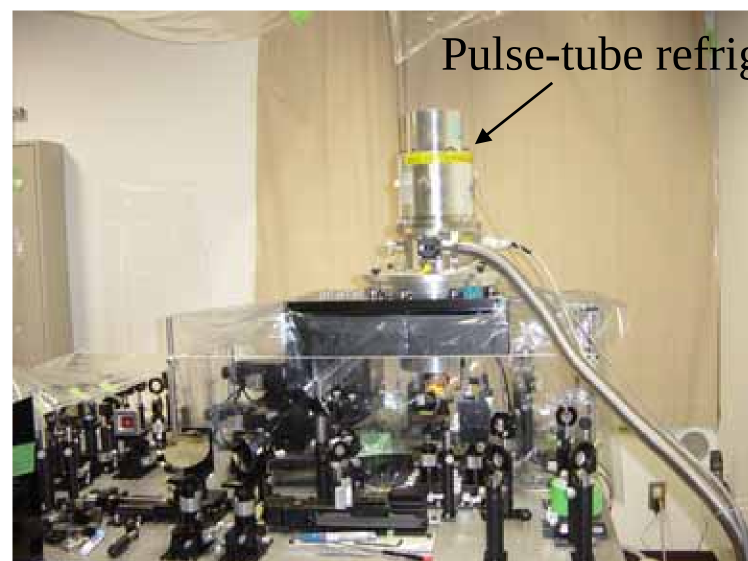


Reflection type

S. Nashima et al., Appl. Phys. Lett. **79** (2001) 3923



System for low-temperature measurements



THz-TDS of Doped Silicon

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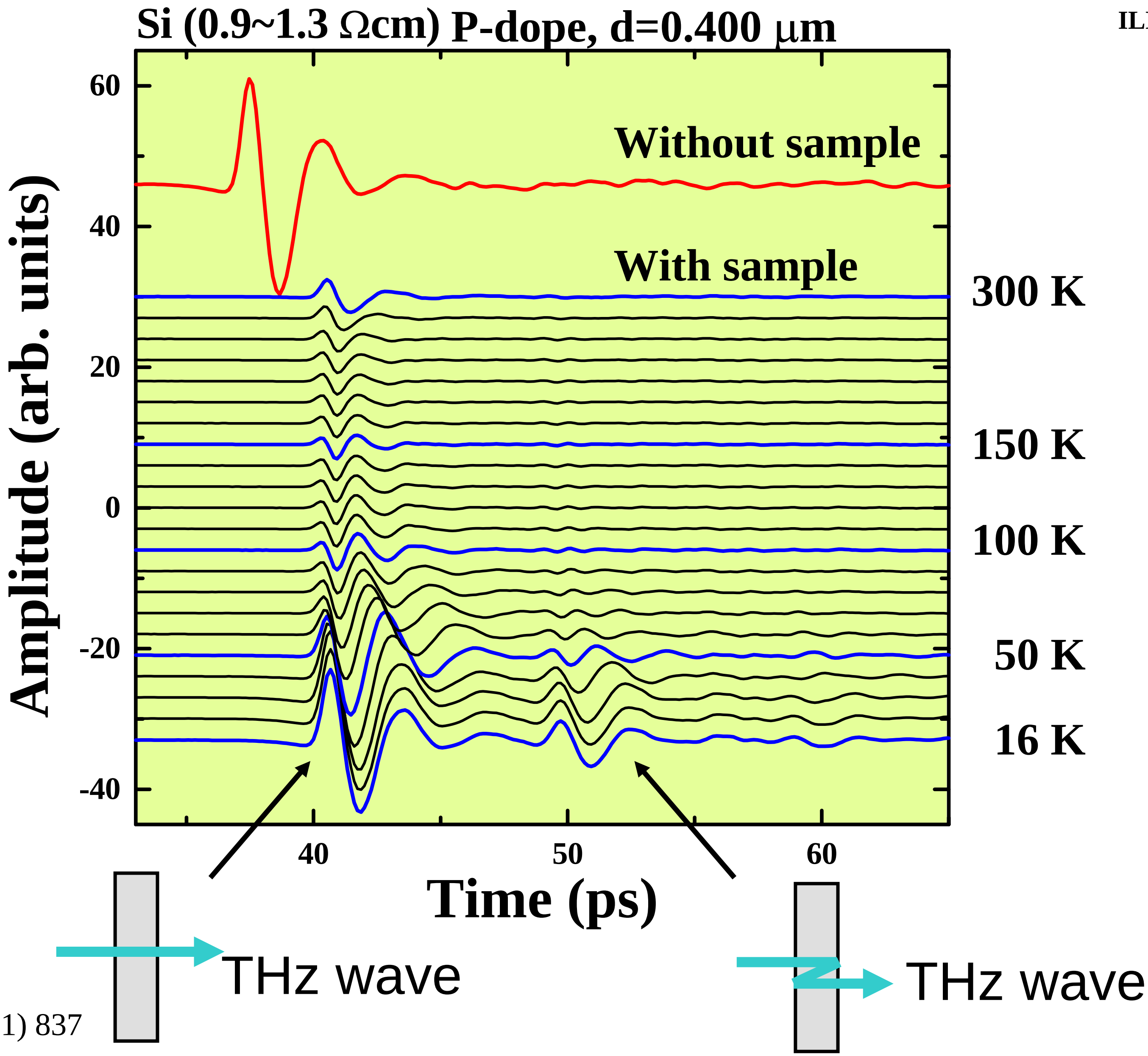

S. Nashima *et al*.,
J. Appl. Phys. **90** (2001) 837

Complex Conductivity Deduced from THz-TDS Data

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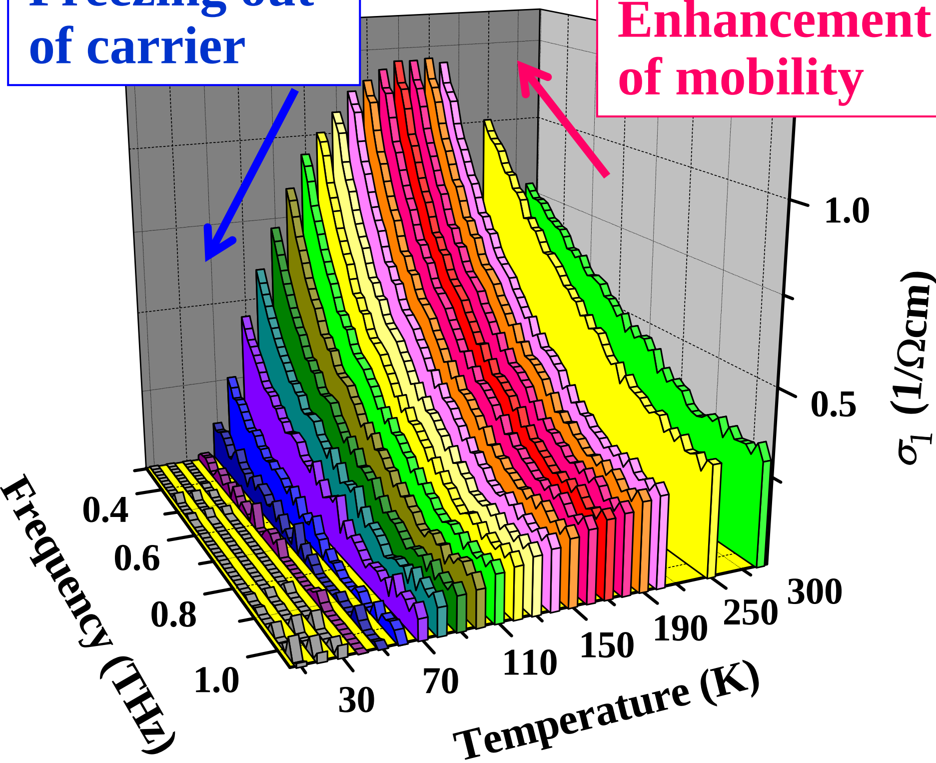
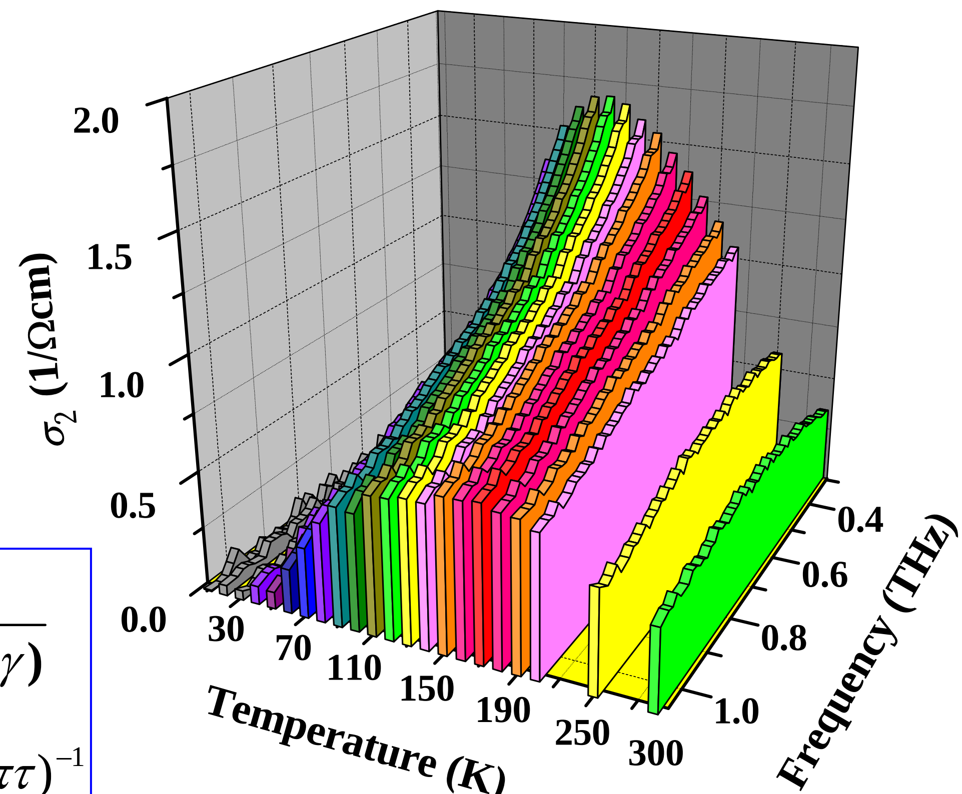
Freezing out of carrier

Enhancement of mobility



$$\sigma_1(\omega)\text{-}i\sigma_2(\omega)$$

$$\tilde{n}^2 = \tilde{\varepsilon}(\omega) = \varepsilon_{\mathrm{Si}} + i\tilde{\sigma}(\omega)/\omega\varepsilon_0$$



Drude model

Dielectric function similar to that of gas plasma

$$\tilde{\varepsilon}(\omega) = \varepsilon_{\mathrm{Si}} - \frac{\omega_{\mathrm{p}}^{\ 2}}{\omega(\omega + i\gamma)}$$

$$\omega_{\mathrm{p}}^{\ 2} = \frac{n_c e^2}{\varepsilon_0 m^*}, \quad \gamma = (2\pi\tau)^{-1}$$

High frequency conductivity σ_1 and σ_2 can be obtained without contact.
By the Drude model fitting, the carrier density and mobility can be deduced.

Time Evolution of Gas Plasma

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JOURNAL OF APPLIED PHYSICS VOLUME 93, NUMBER 7 1 APRIL 2003

Plasma characterization with terahertz time–domain measurements

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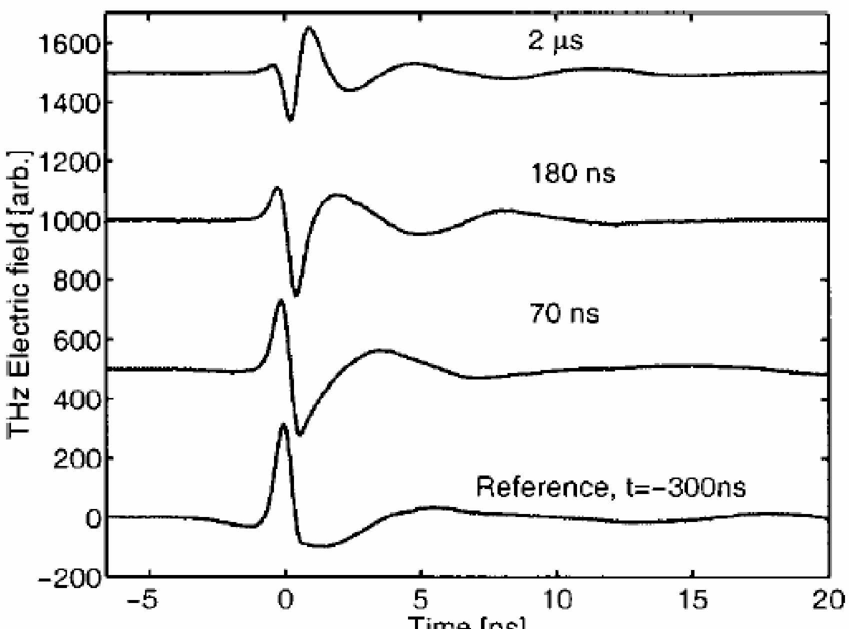
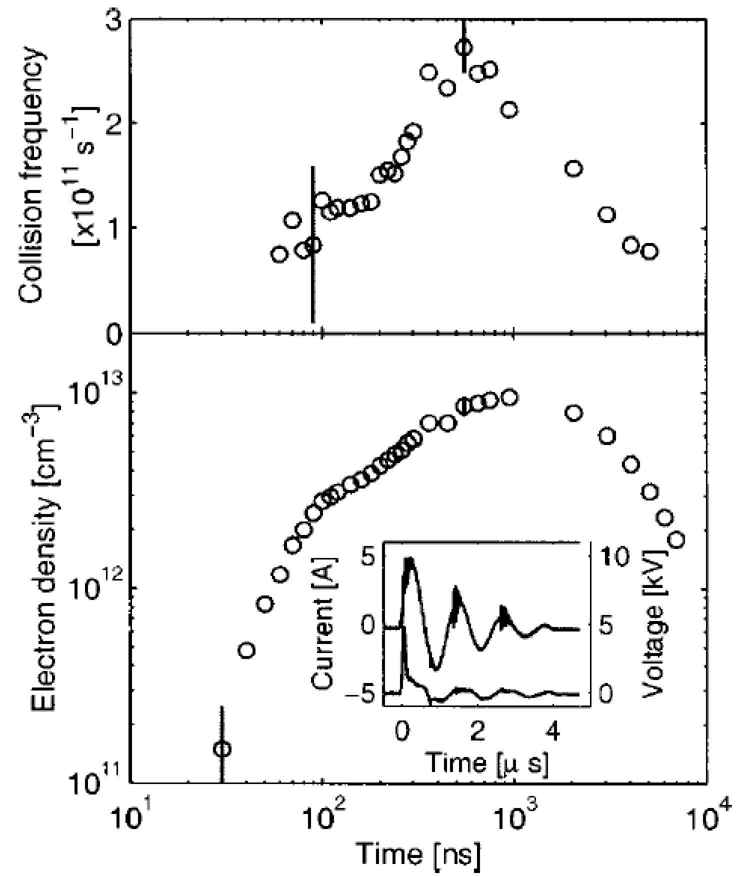
Department of Physics and Applied Physics, University of Strathclyde, Glasgow, G4 0NG, United Kingdom

$$\epsilon=\left(1-\frac{\omega_p^2}{\omega^2+\nu^2}\right)-i\left(\frac{\nu}{\omega}\,\frac{\omega_p^2}{\omega^2+\nu^2}\right)$$

$$\omega_p=\sqrt{n_e e^2/\epsilon_0 m_e}$$

He discharge plasma
15 cm long and 2 cm diameter plasma tube





Probed by delayed THz pulses after discharge

THz Magneto-optical Measurement System

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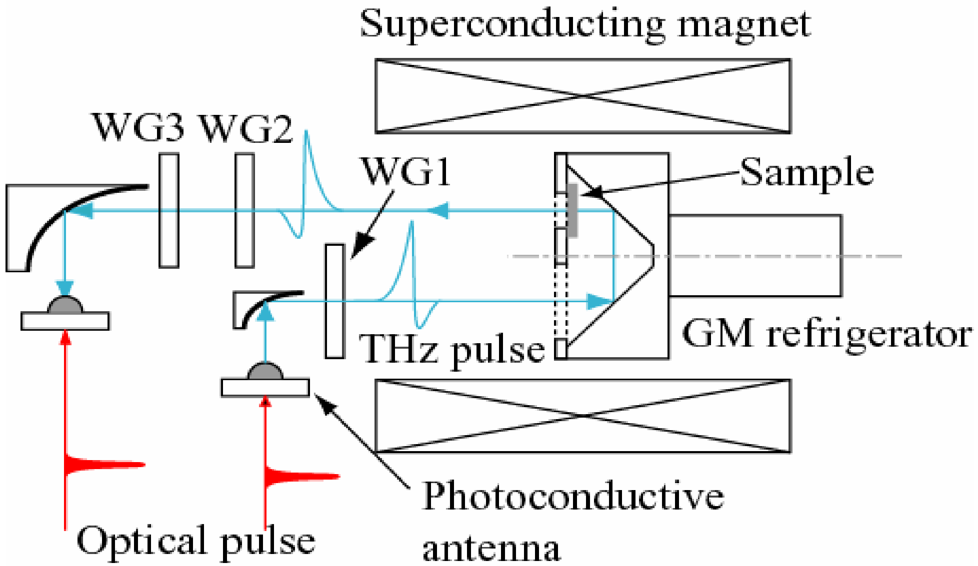
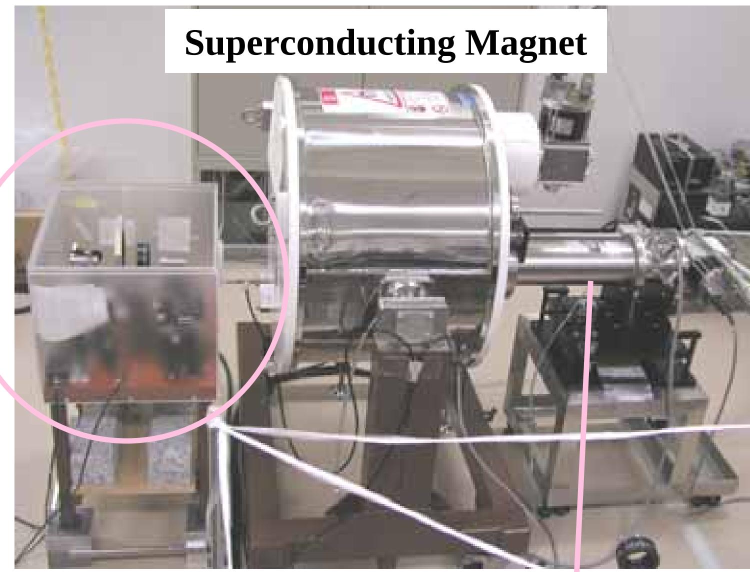
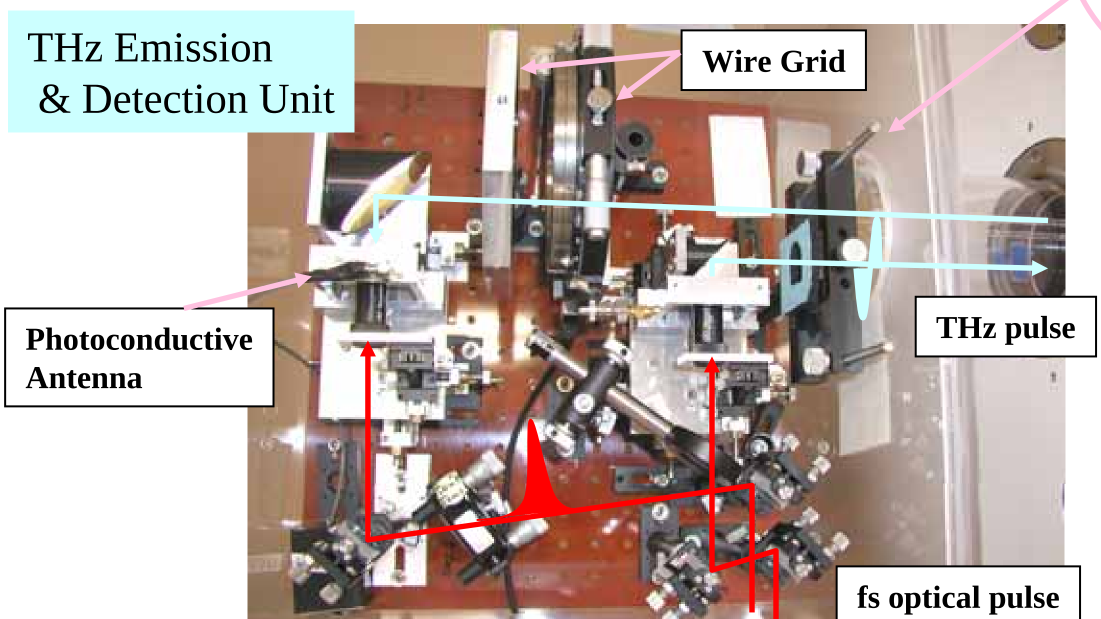
High magnetic field (10 T) and low temperature (5 K)

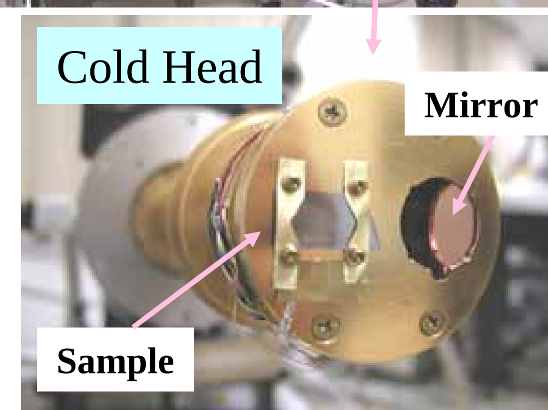


Rotation of the Wire grid polarizer

⇨ The polarization analysis







THz Magneto-optical Effect of Si-doped GaAs

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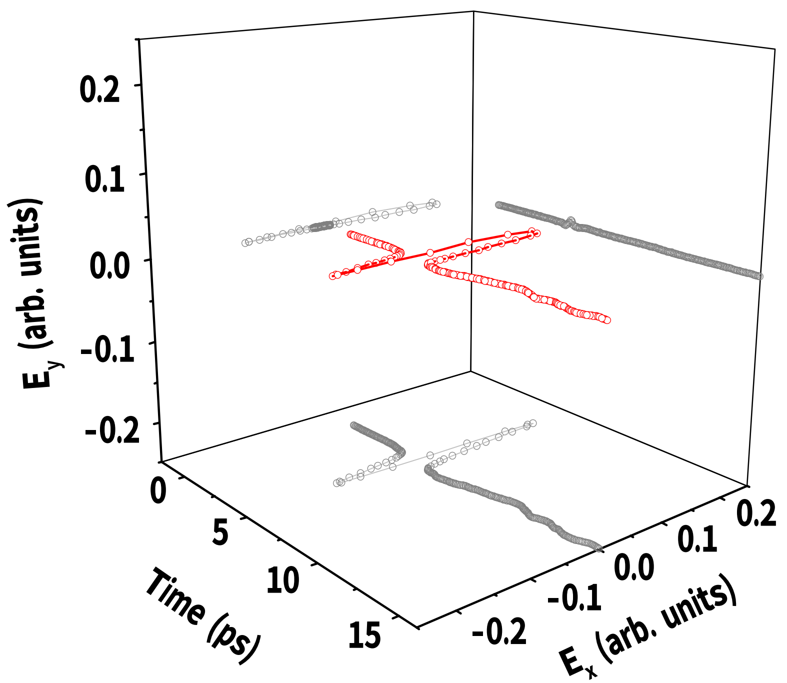
10 T, 5 K

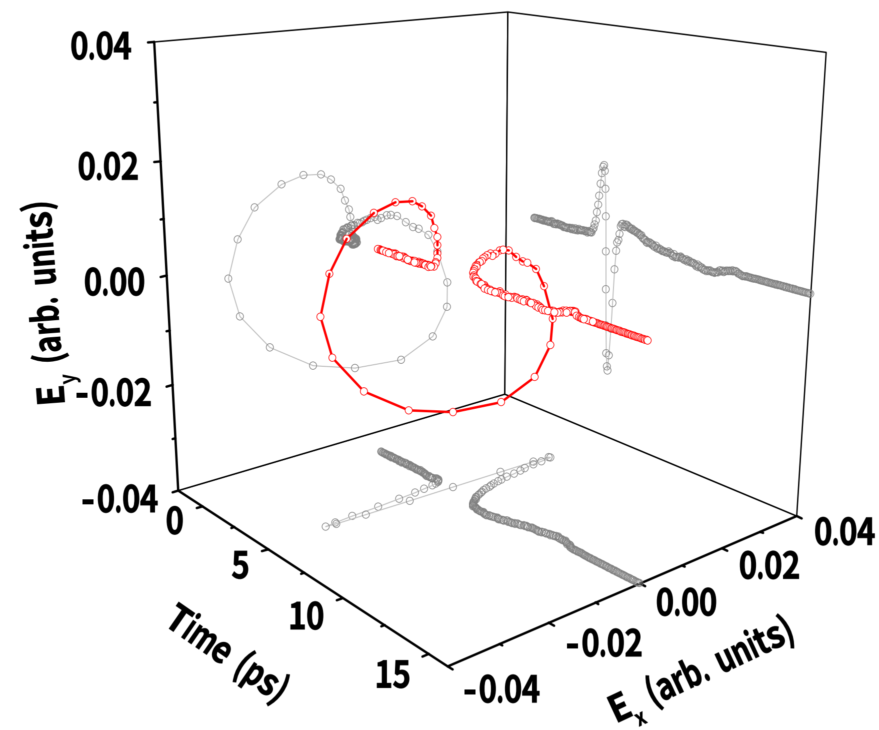
Si-doped GaAs wafer (100), *d* = 0.371 mm
Carrier density 1.34×10^{16} cm^{-3} , Mobility 3400 cm^2/Vs at R.T.

Faraday effect

Incident THz pulse



Si-doped GaAs



THz waveform —F.T.→

- Ellipticity
- Rotation angle

Temperature Dependence

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B = 10 T

High temperature

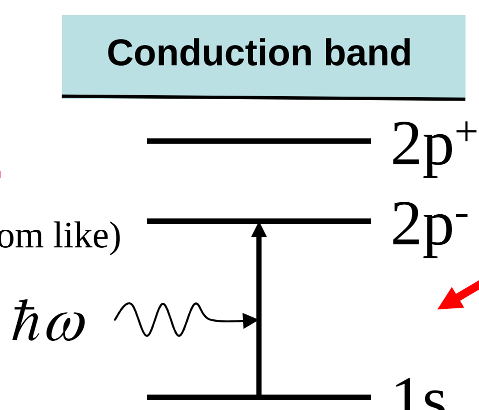
Black solid line : Drude fitting

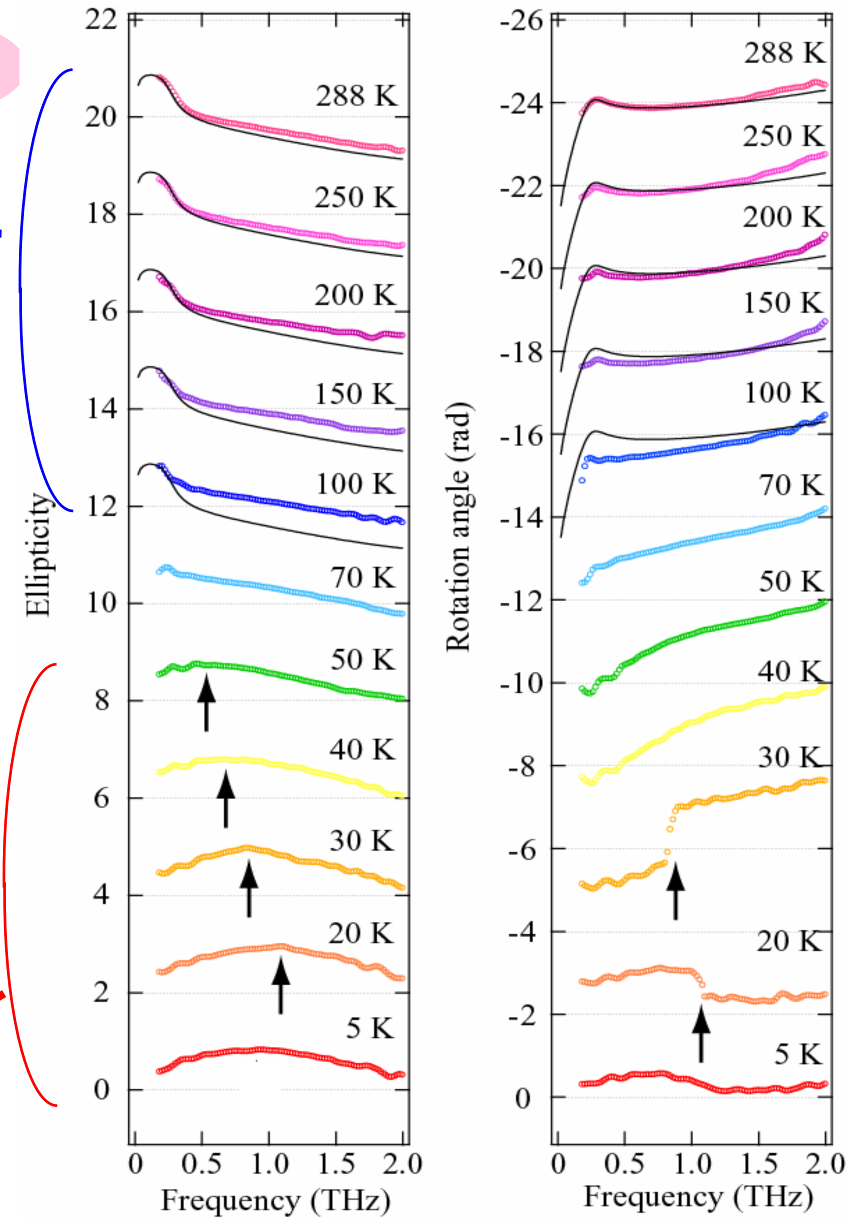
($n_c = 1.34\times10^{16}$ cm^{-3}, $\tau = 0.13$ ps)

Low temperature

Si-donor

(Hydrogen atom like)





Measurement System for Gases

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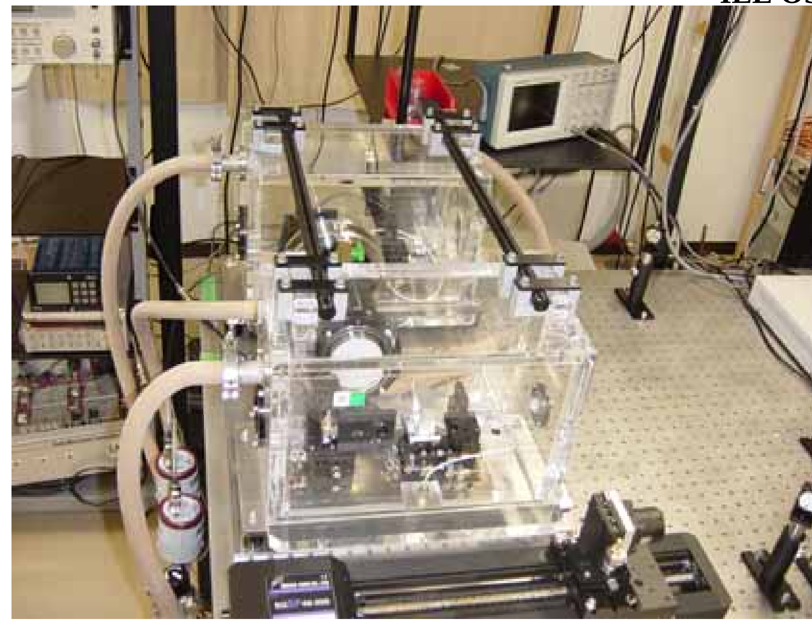

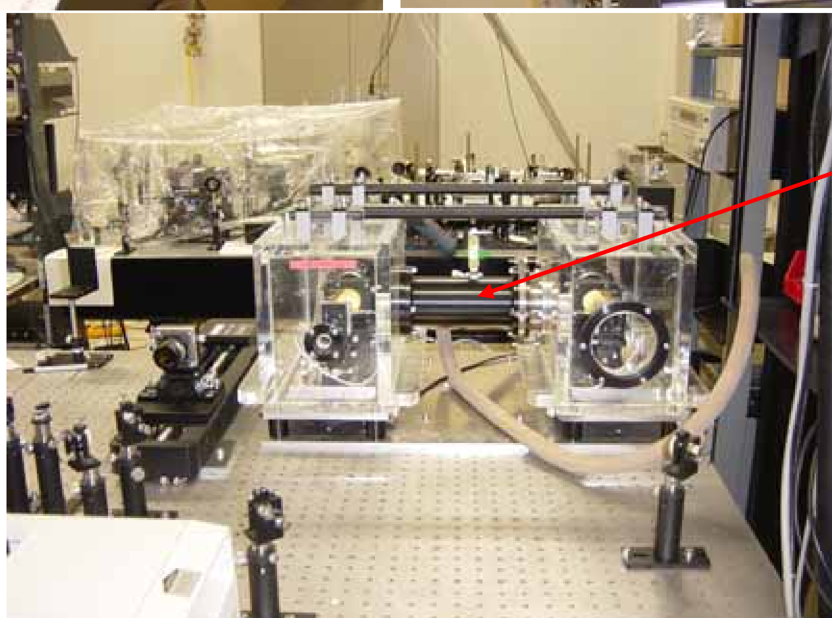

Gas cell

Transmission Spectrum of Methanol Gas

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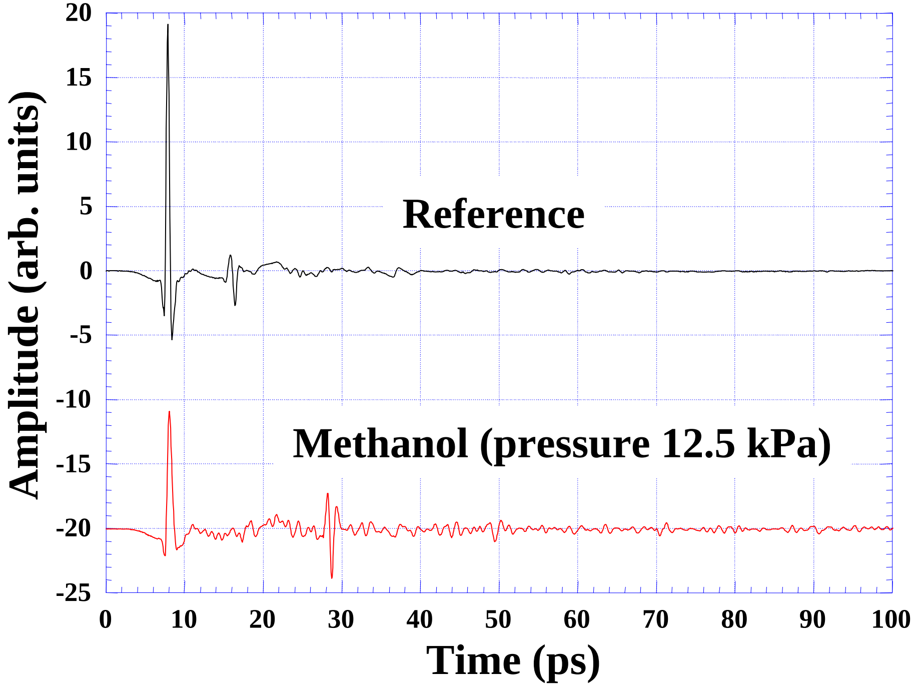
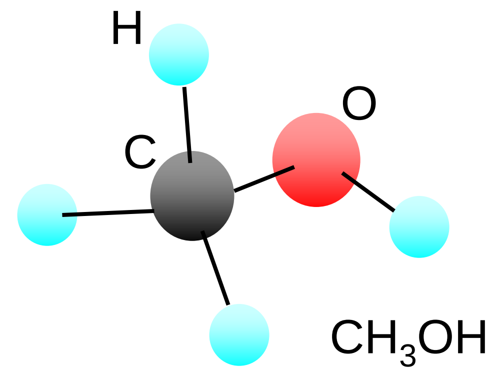
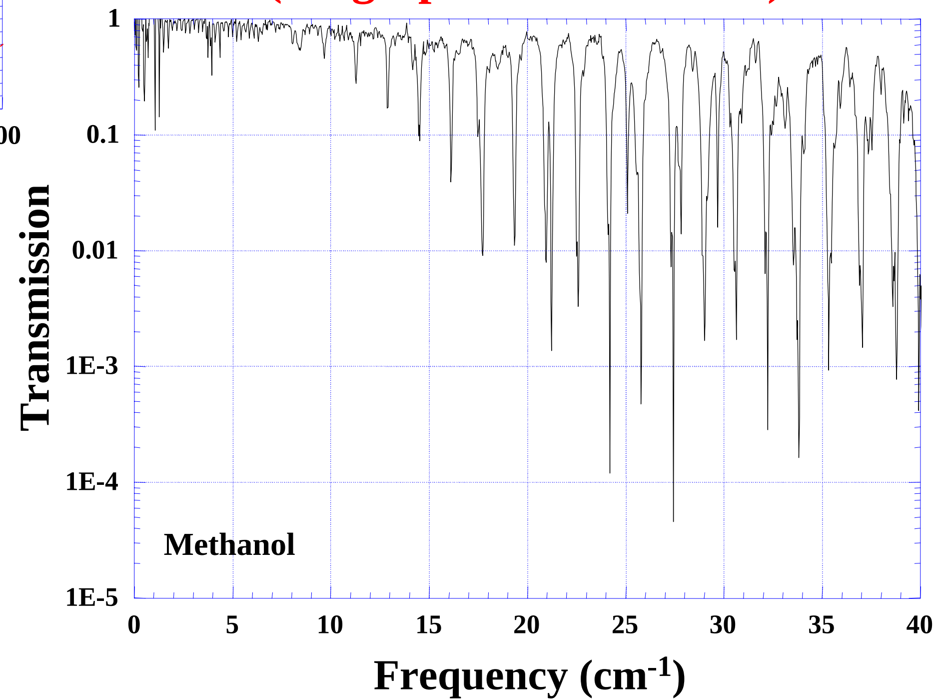
Time-domain wave form



Rotational transitions



Transmission spectrum
(Fingerprint of molecule)



1 THz = 33 cm^{-1}

Identification of molecular gas species is possible.

4. THz imaging

Two Types of Imaging Methods

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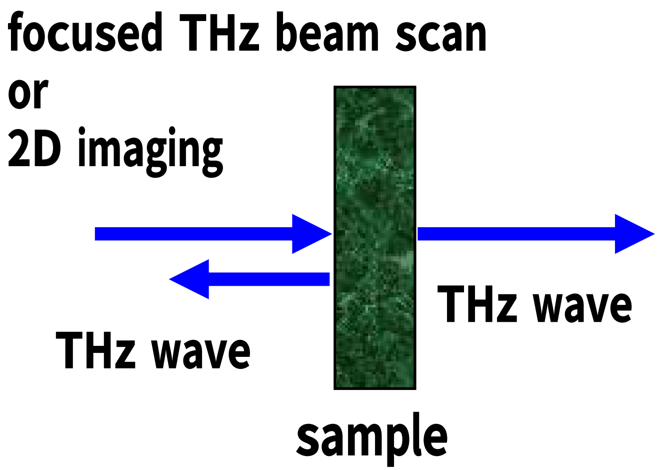
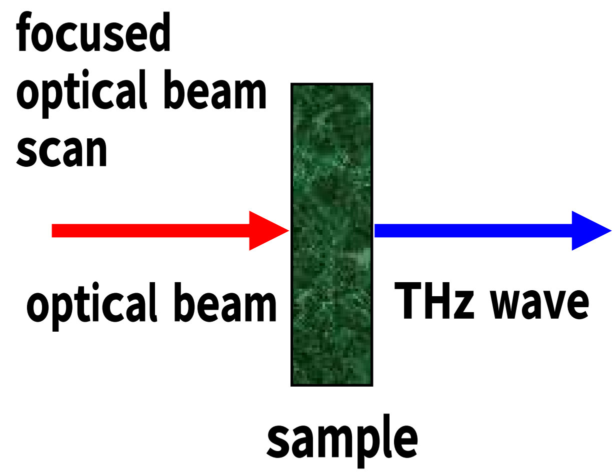
THz transmission and reflection imaging	THz emission imaging



- Conventional imaging method
- Applicable to most samples



- Limited to samples emitting THz waves
- Imaging method unique to THz waves

Distribution of surface field in semiconductors
Distribution of supercurrent in superconductors

Pioneering Work of THz Imaging

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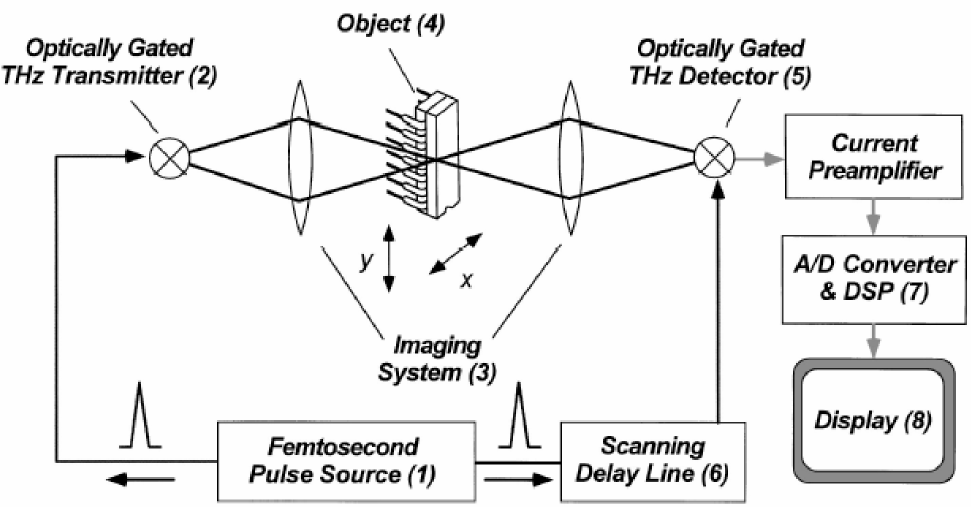
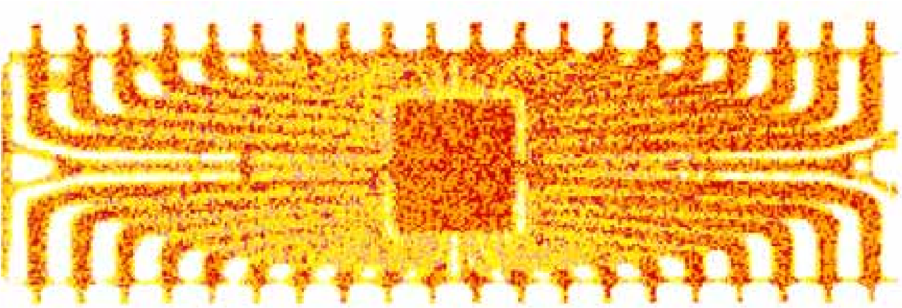
B. B. Hu and D. H. Auston, Opt. Lett. **20** (1995) 1716

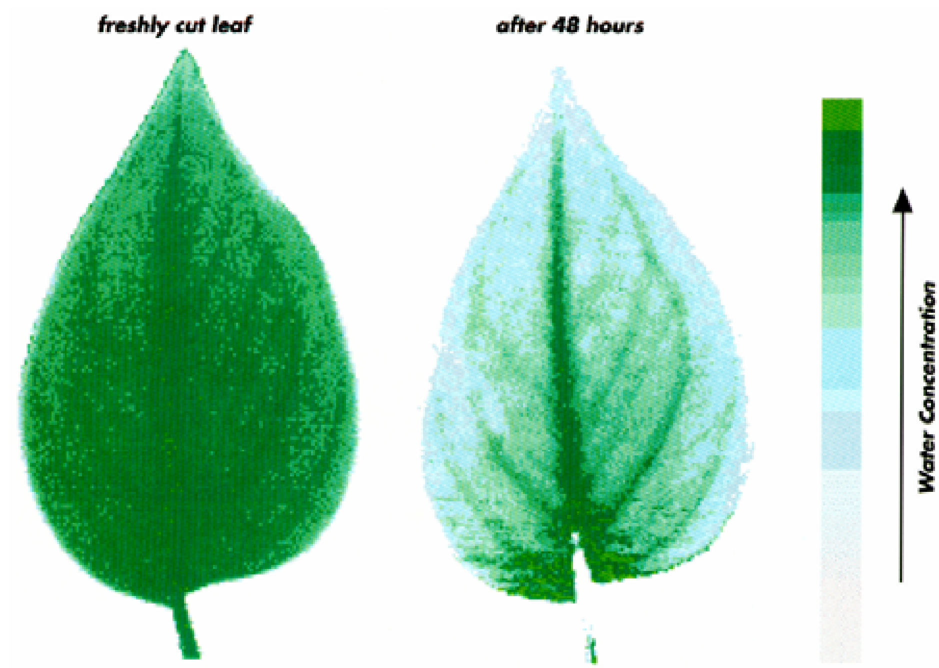


Characteristics of THz waves

- ◯ absorbed strongly by liquid water
- ◯ plastic, paper, ceramics transmit THz waves
- ◯ reflected completely by metals
- ◯ cannot transmit long distance in air



IC package



Leef

Spectrum of Plastic Bomb

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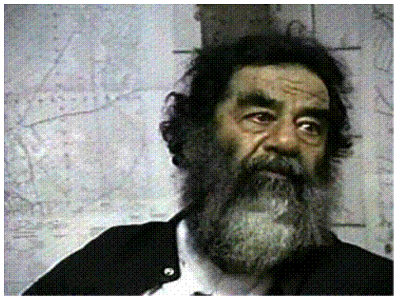
Newspaper “Yomiuri”

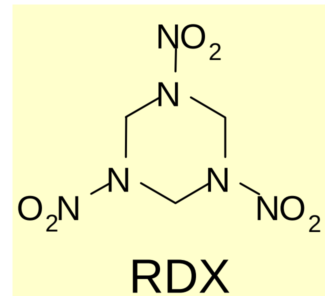
Collaboration with Osaka Prefectural Police



Although Saddam was captured ..

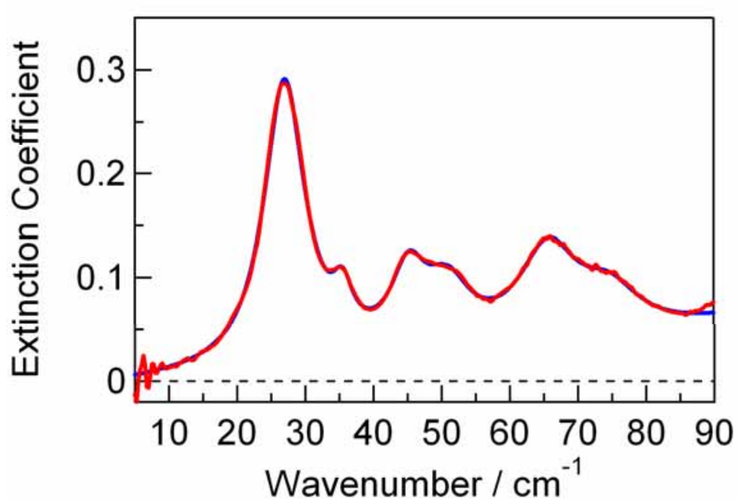
Dec. 17, Baghdad

Threatening of terrorist bombing is still continuing.



Detection of plastic bomb C-4

Detectable of C-4 in mail



K. Yamamoto *et al.*,
Jpn. J. Appl. Phys. **43** (2004) L414

Imaging of Plastic Bomb in Mail

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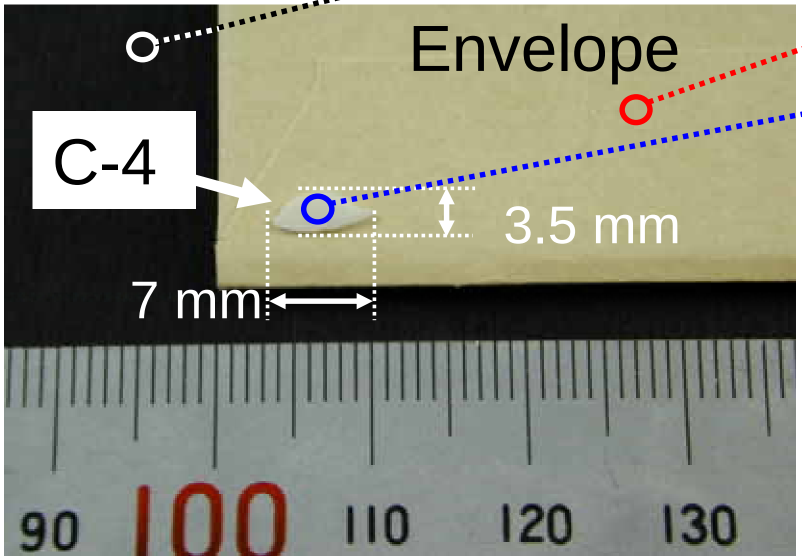

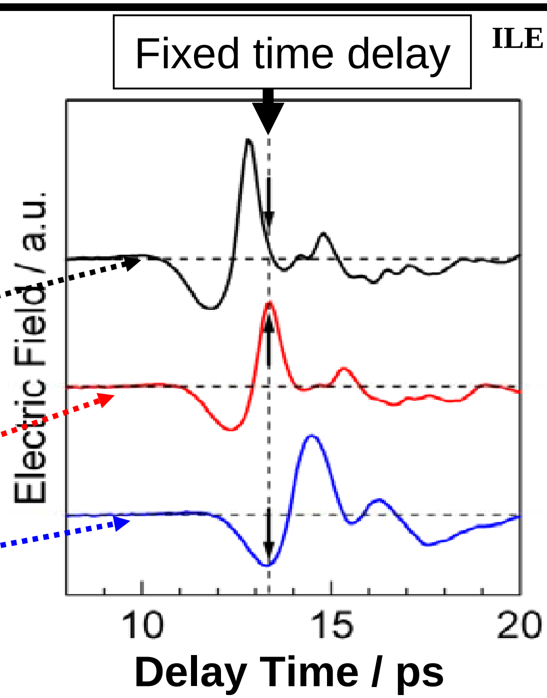

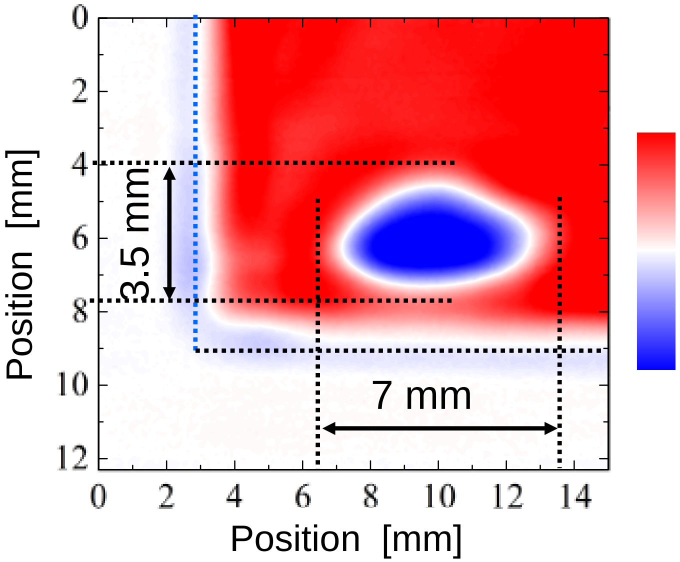

High-speed (Real-time) THz Imaging System

F. Miyamaru *et al*., Jpn. J. Appl. Phys. **43** (2004) L489

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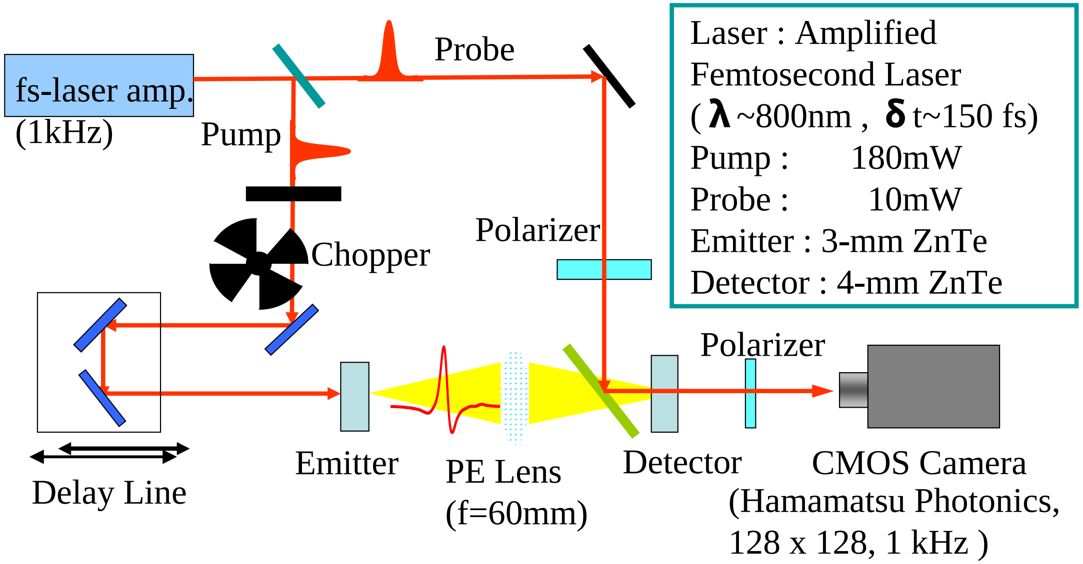
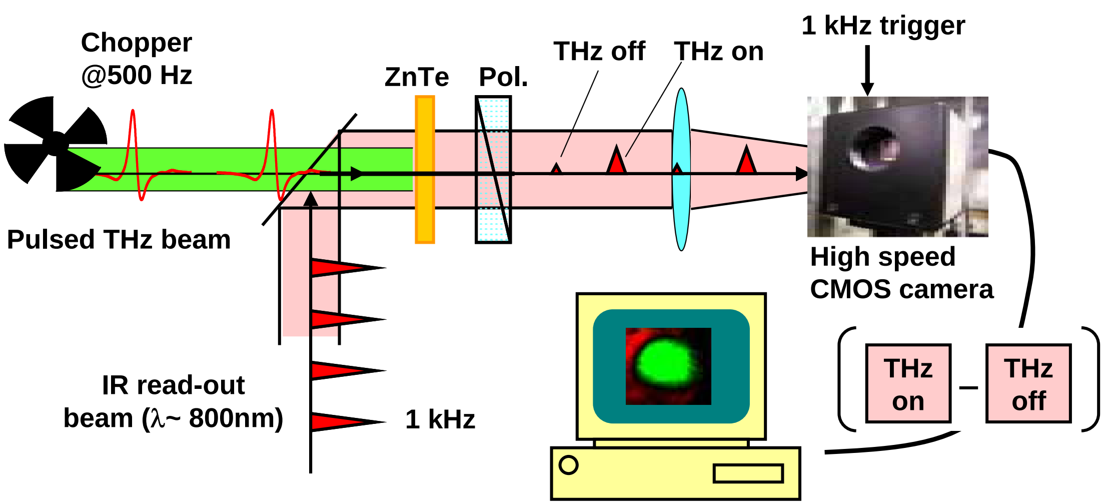
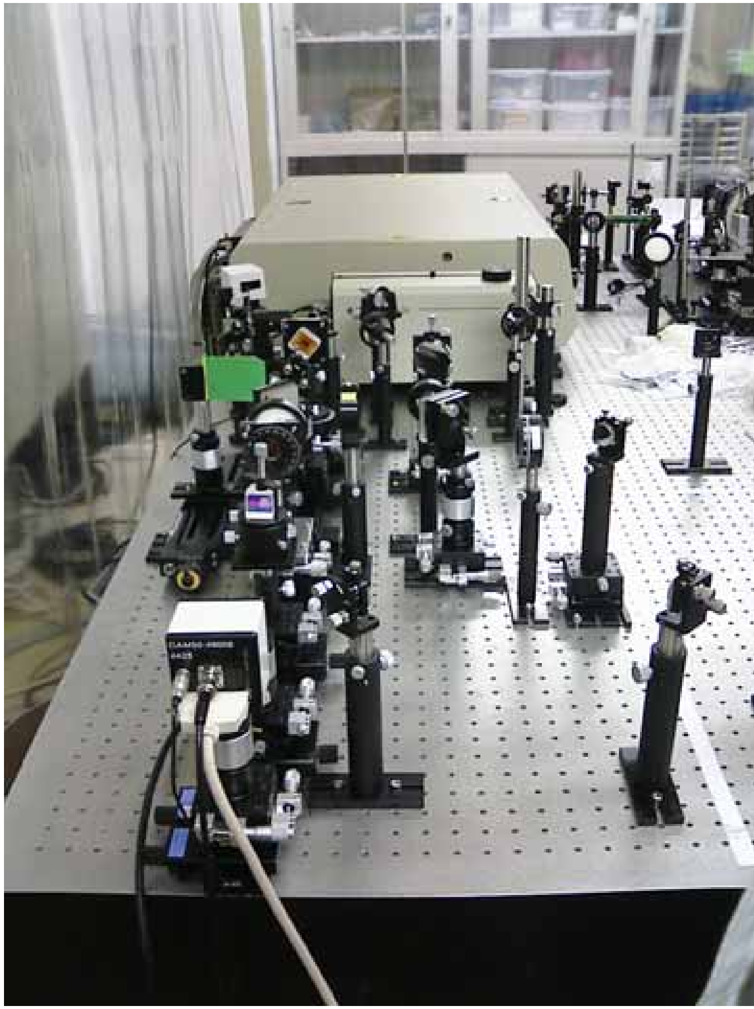


Original idea by X. –C. Zhang

Q. Wu, T.D. Hewitt, and X.-C. Zhang , Appl. Phys. Lett. **69** (1996) 1026





500 frames/s (2 ms/frame)

Imaging of Contents in Envelope

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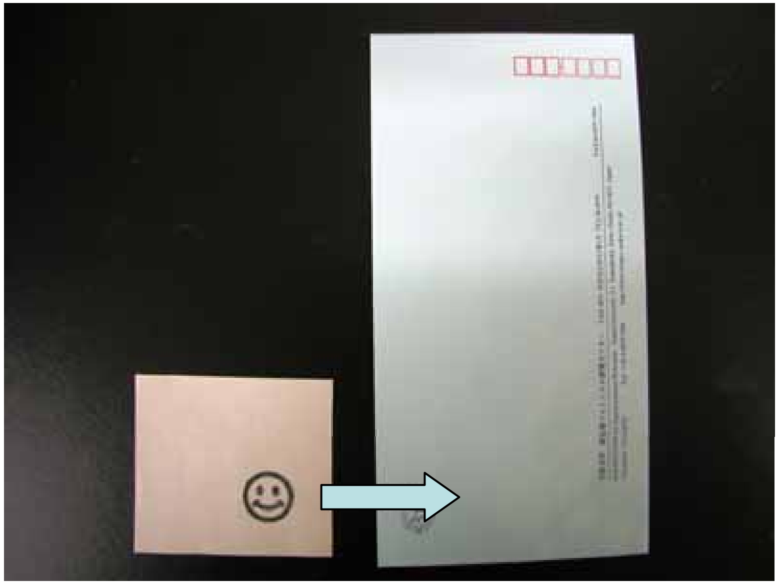
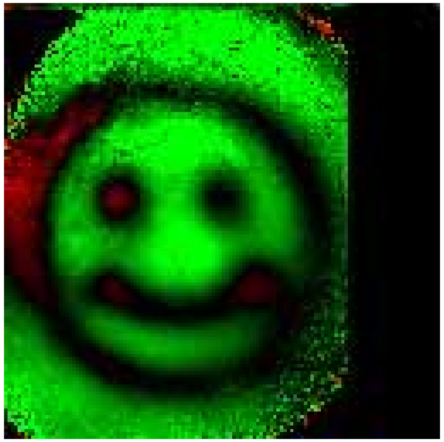
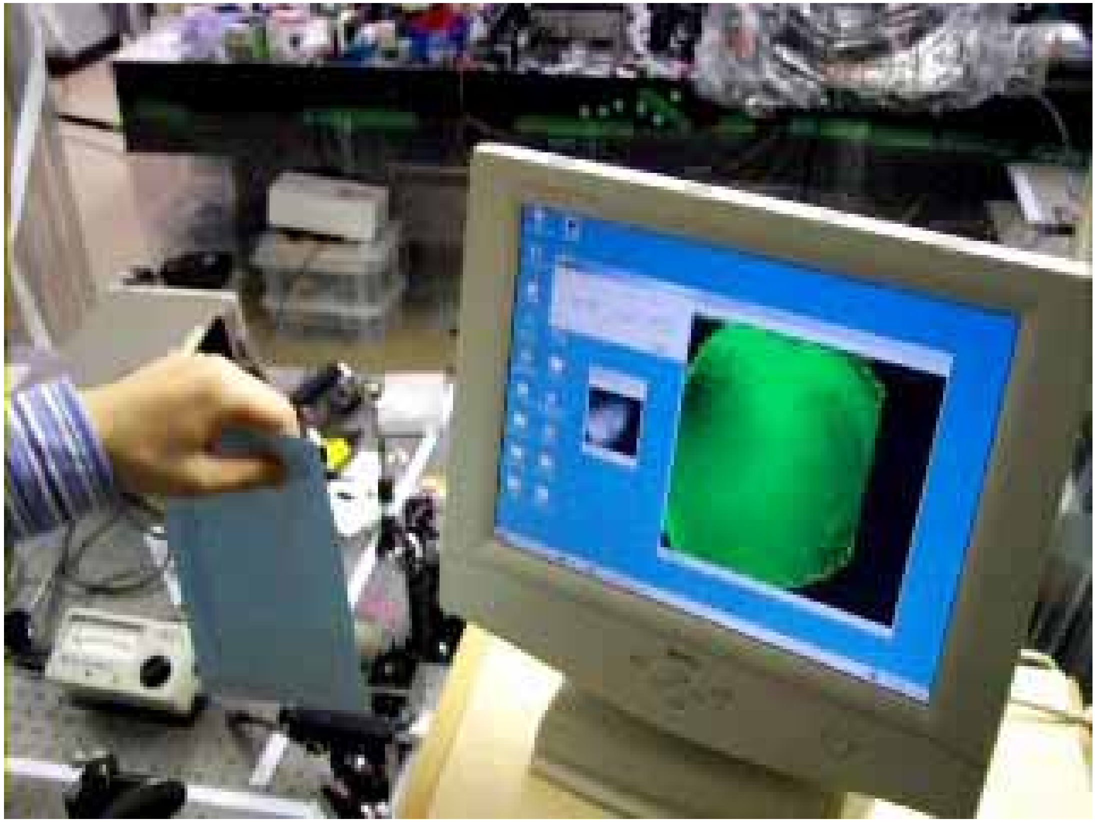
THz wave (T-ray) is safe for human bodies in contrast to X-ray.







Relection Type Imaging System

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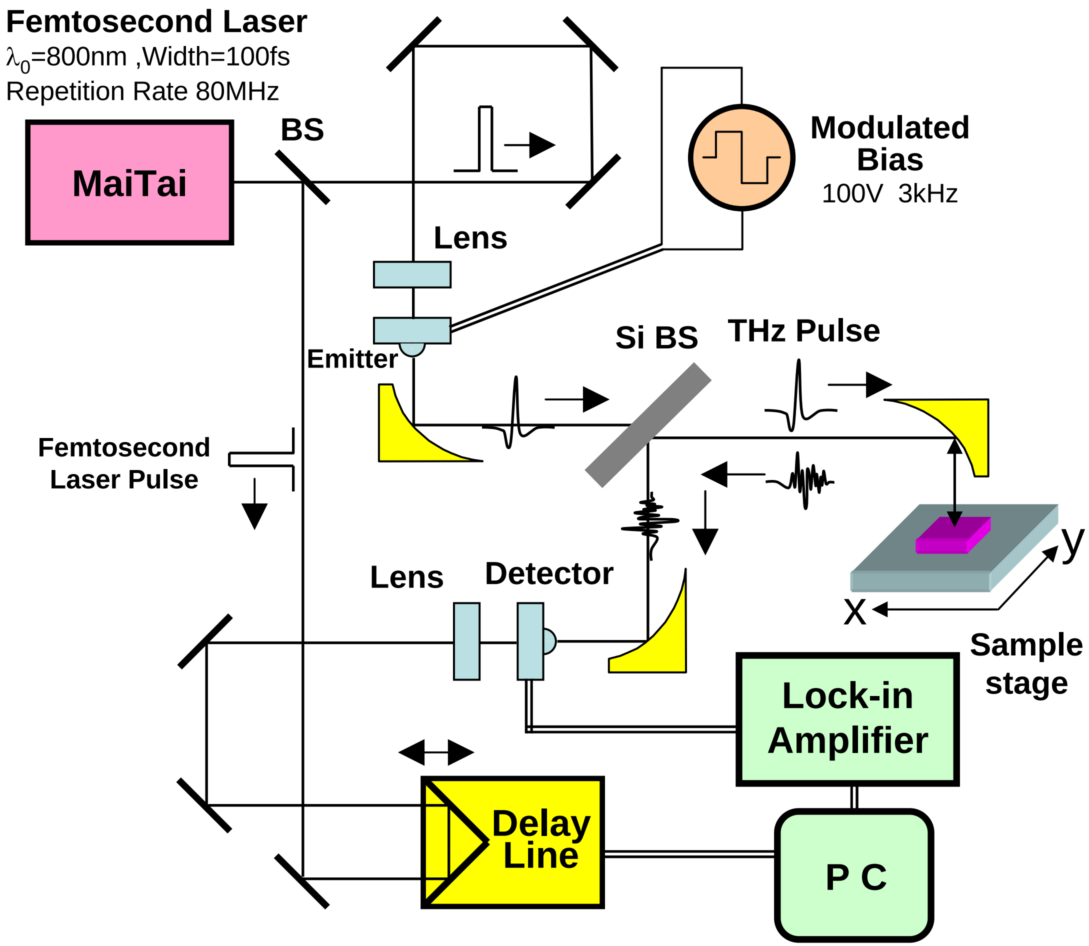
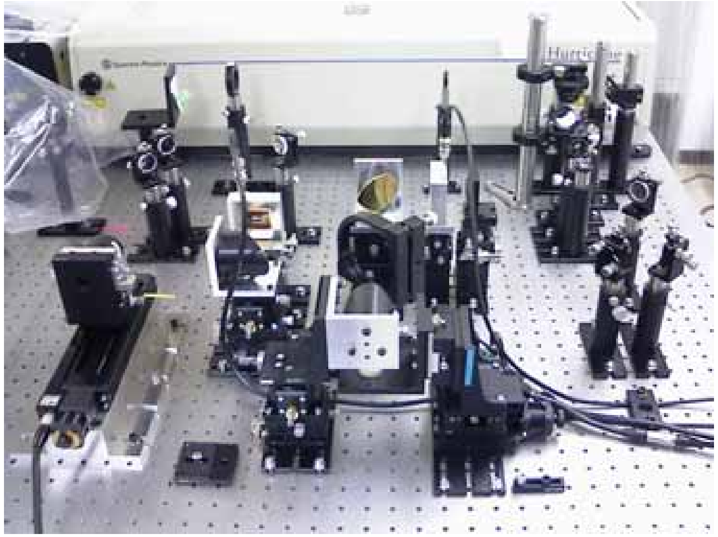
Raster scan type reflection imaging system





Reflection Image of Coin

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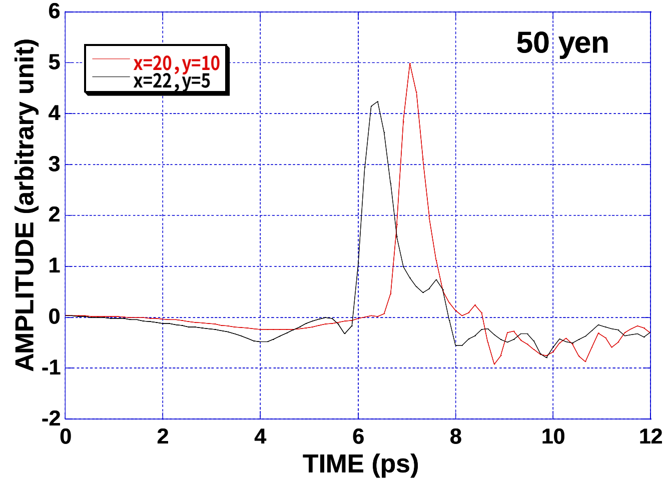
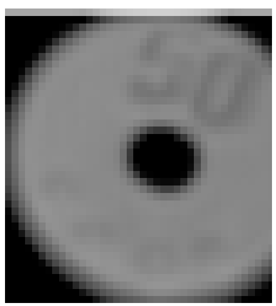
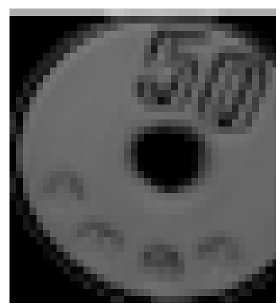
50 yen Japanese coin



0.23THz

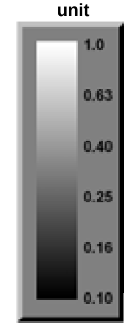


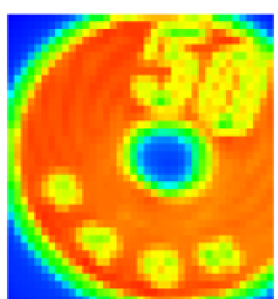
0.46THz



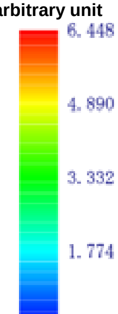
0.69THz

arbitrary unit

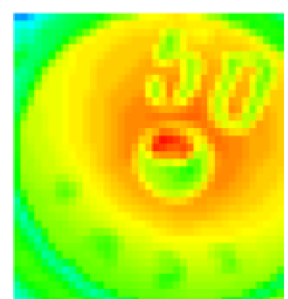




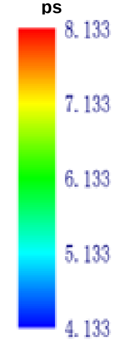
arbitrary unit



Amplitude



ps



Time delay

Tomographic Image of Finger

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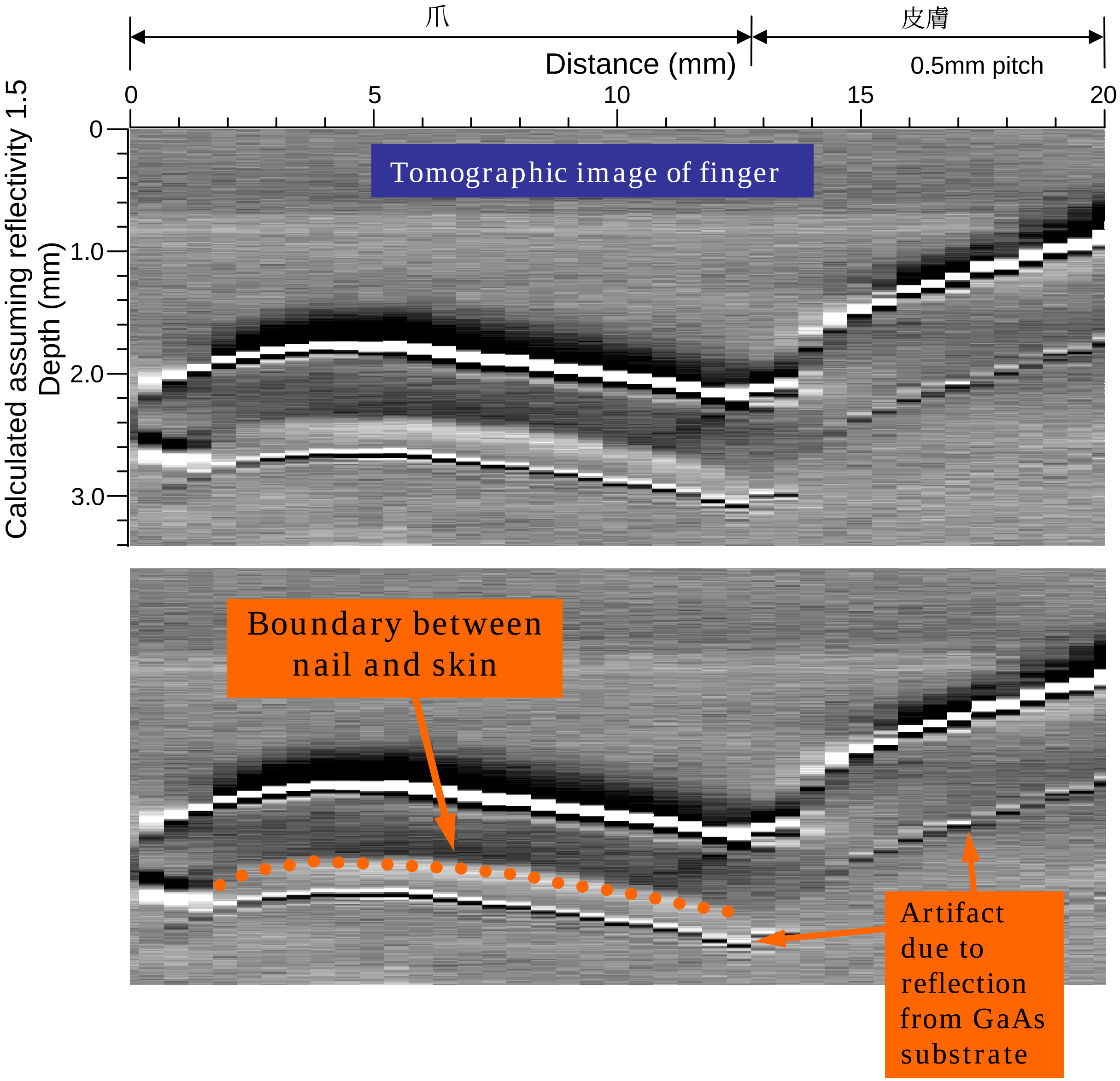
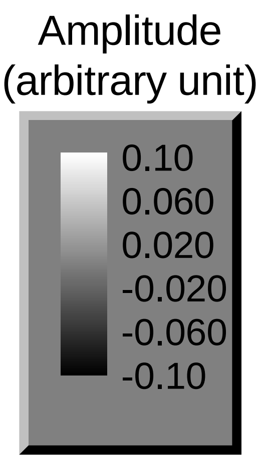
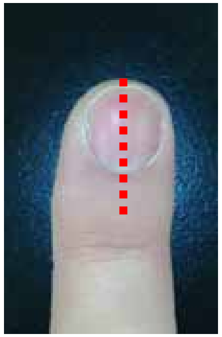


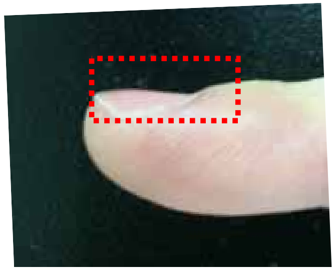


Top view



Broken red line : scanning range

Side view

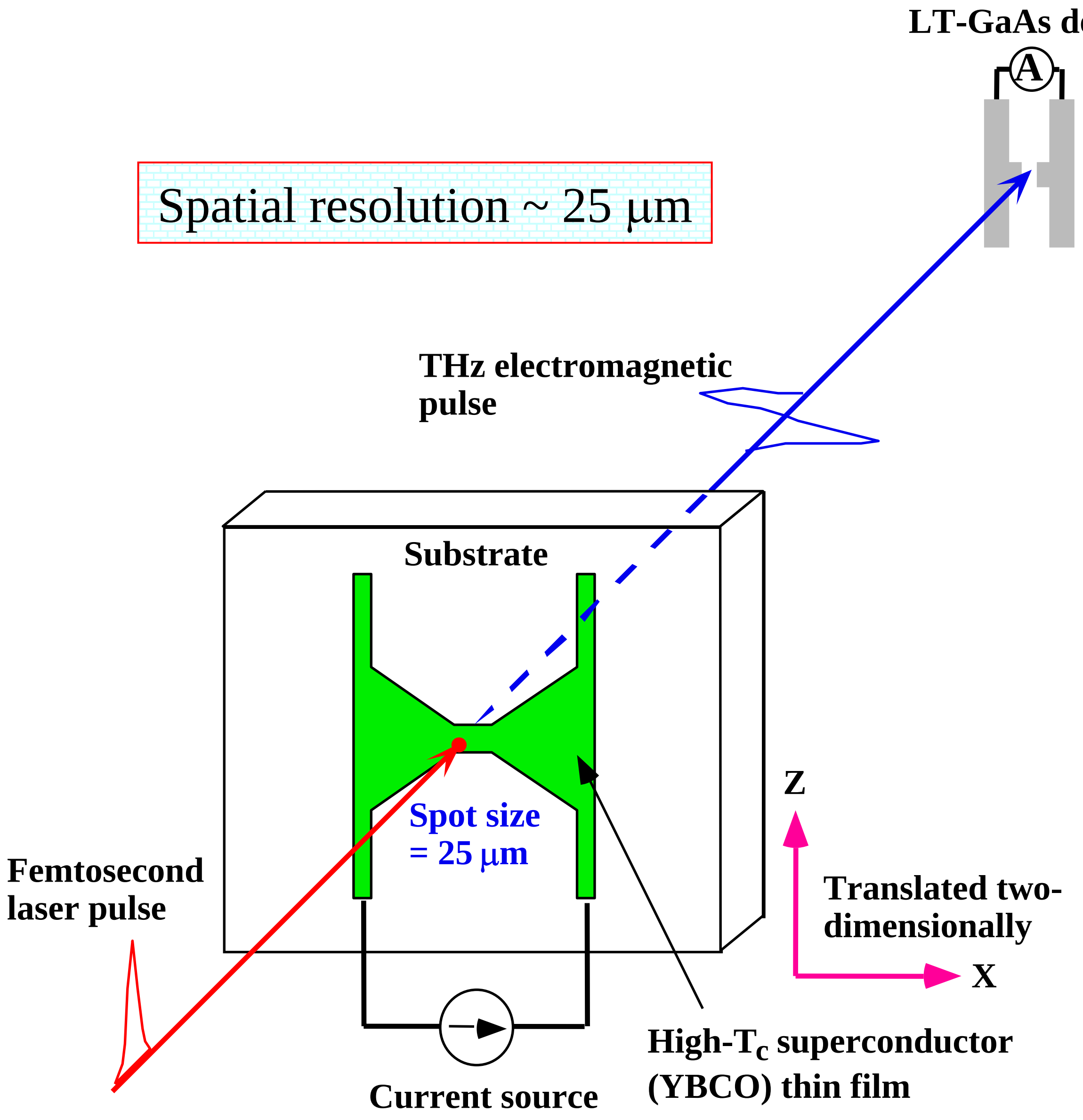


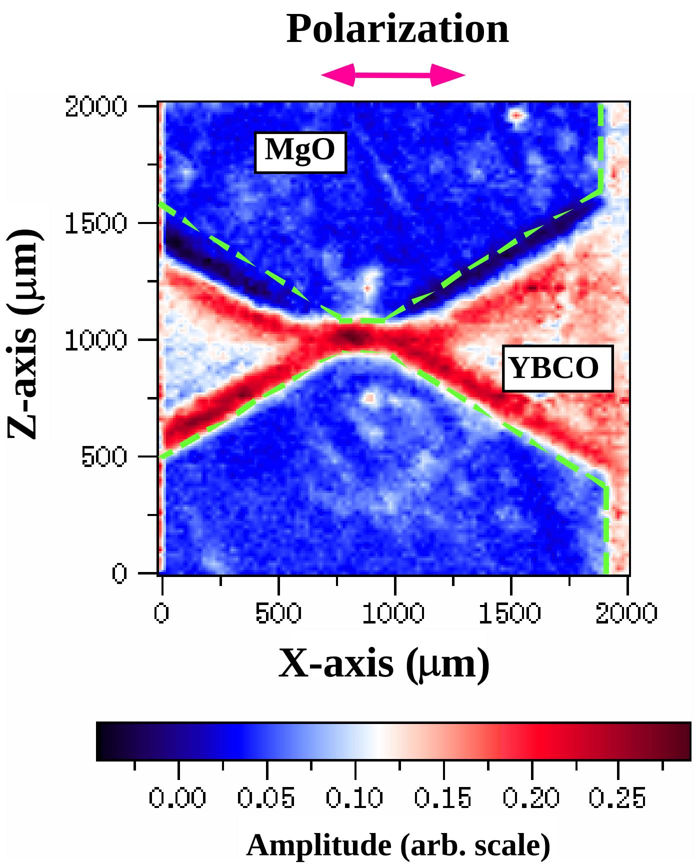
Red square : tomographic imaging region

Supercurrent Distribution by THz Radiation Imaging

ILE OSAKA

Spatial resolution ~ 25 μm





40 mW exc.
I_B = 330 mA

S. Shikii *et al*., Appl. Phys. Lett. **74** (1999) 1317

Future Application to ITER

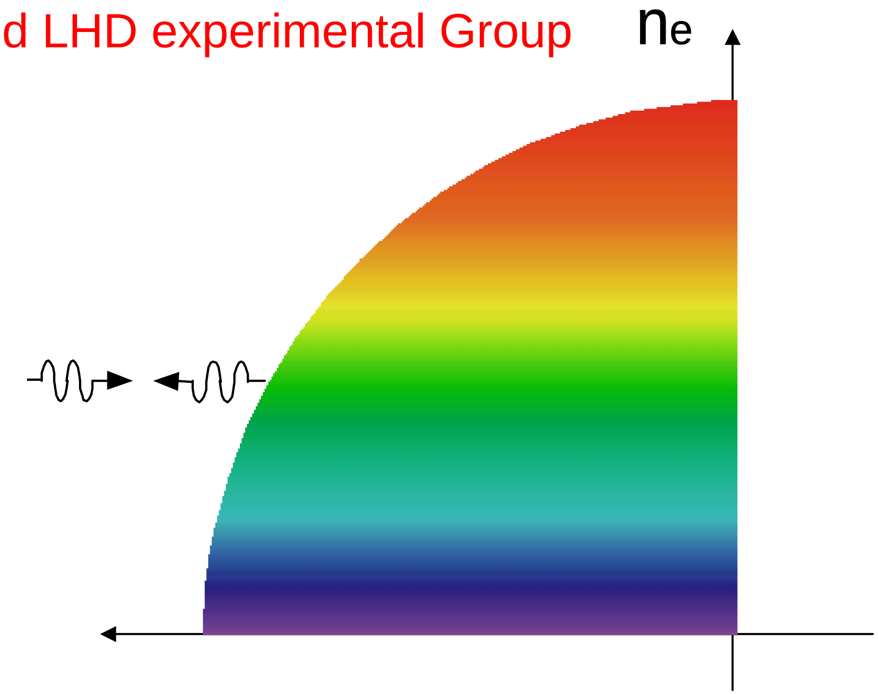
ILE OSAKA

Ultra-short Pulsed Radar Reflectometer

Cutoff frequency

$$f_{pe} = \frac{1}{2\pi}\sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}}$$

T.Tokuzawa, K.Kawahata, and LHD experimental Group



Delay time of each frequency component corresponds to the plasma density.

Ka-band Ultra-short Pulsed Radar Reflectometer
10ch (28〜39 GHz)

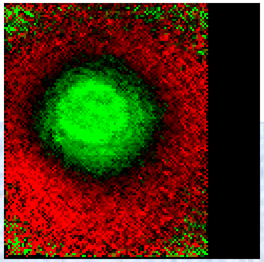
For ITER, very high frequencies are necessary for full coverage – to ~ 1 THz

THz radiation excited by femtosecond laser is a possible solution.

Problems : low intensity, deflection of reflected beam

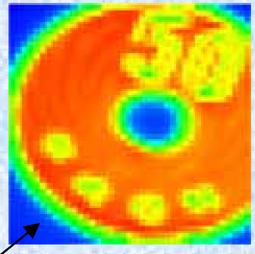
Summary

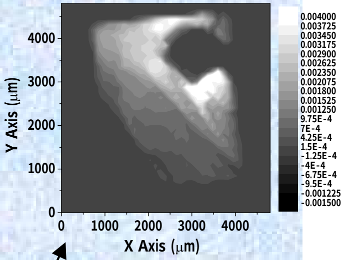
of Imaging and Its Applications



Characteristics of THz Waves

- ○ absorbed strongly by liquid water
- ○ plastic, paper, ceramics transmit THz waves
- ○ reflected completely by metals
- ○ cannot transmit long distance in air

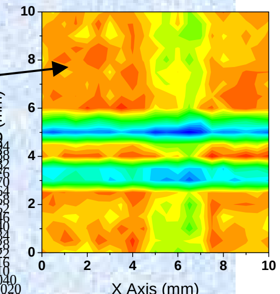


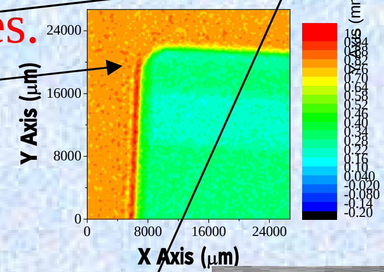


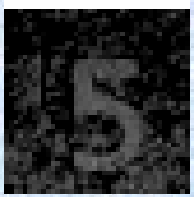
● Raster scan type and 2D real time imaging systems are constructed.

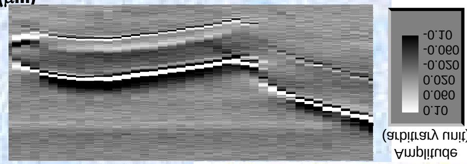
● The imaging systems are applied to various samples.

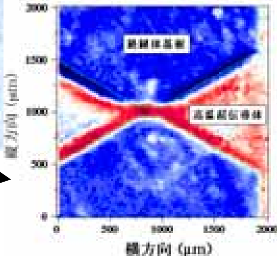
- ○ metal wires
- ○ magnetic cards
- ○ plastic bomb in mail
- ○ coins and watermarks
- ○ finger (tomographic image)
- ○ electric field distribution on semiconductor surfaces
- ○ supercurrent distribution











Next step is real world applications including plasma diagnostics