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*WINTER COLLEGE ON
SPECTROSCOPY AND APPLICATIONS*

(8 - 26 February 1999)

"THz-Spectroscopy"

*1. Generation and Coherent Detection
of fs-THz-Radiation*

presented by:

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These are preliminary lecture notes, intended only for distribution to participants.

THz-Spectroscopy

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Trieste, Italy



R. Beigang

Fachbereich Physik
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1. Generation and coherent detection of fs-THz-Radiation
2. From fundamental to industrial applications
3. Literature

1. Generation and coherent detection of fs-THz-Radiation

1.1 Introduction

1.2 Generation of THz radiation

1.3 Fs technology for THz generation

1.4 THz emitters

1.5 Coherent detection of THz radiation

1.6 Fs-THz-systems

1.7 Properties and design considerations

1.8 Spectral information

THz-Spectroscopy



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1. Generation and coherent detection of fs-THz-Radiation
2. From fundamental to industrial applications

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Introduction

Why ultrashort light pulses ?

- o Application cannot be performed without ultrashort light pulses.
- o Use of ultrashort pulses has certain advantages compared to other techniques:
 - cheaper
 - better S/N
 - more flexible
 - lower power consumption
 - compact

⇒ use of ultrashort pulses also for applications which are “extremely slow”

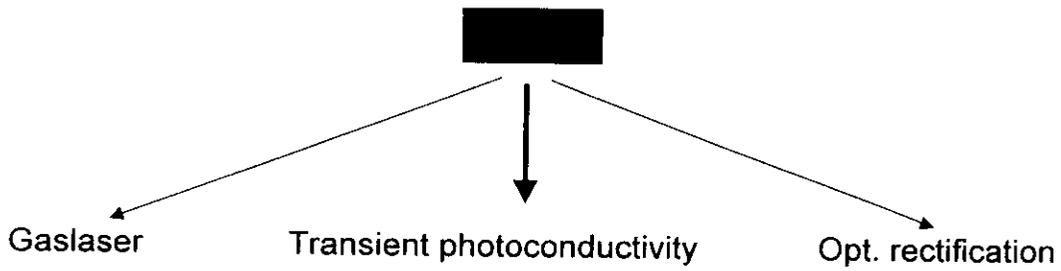
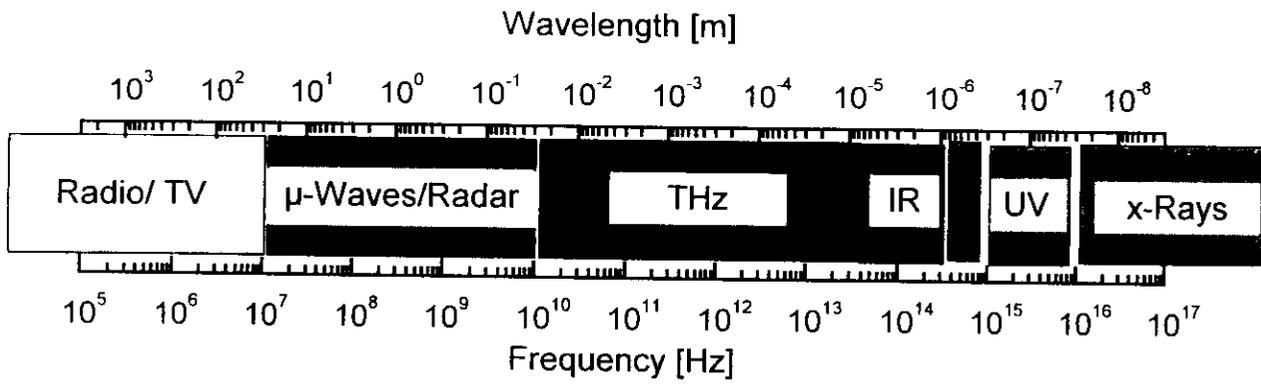
⇒ **Requirements: cost effective and reliable fs-systems**



Introduction

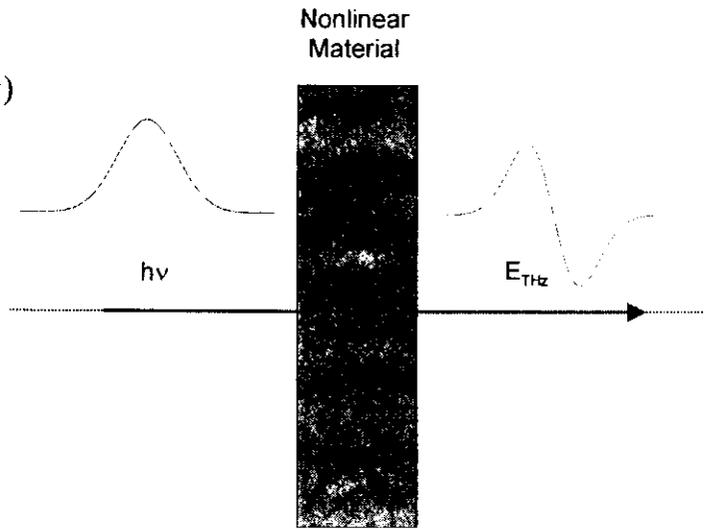
- o Generation of fs THz-radiation using ultrashort pulses:
 - Transient photoconductivity
 - Optical rectification
- o Three key components for a THz-system:
 - fs light source
 - THz transmitter and
 - THz receiver
- o “Real world” applications require compact, “turn key”, reliable systems
 - ⇒ diode pumped solid state laser
- o fs THz-generation using a diode laser pumped Cr:LiSAF and photoconductive switches for applications in multi component gas monitoring

Generation of fs-THz-radiation

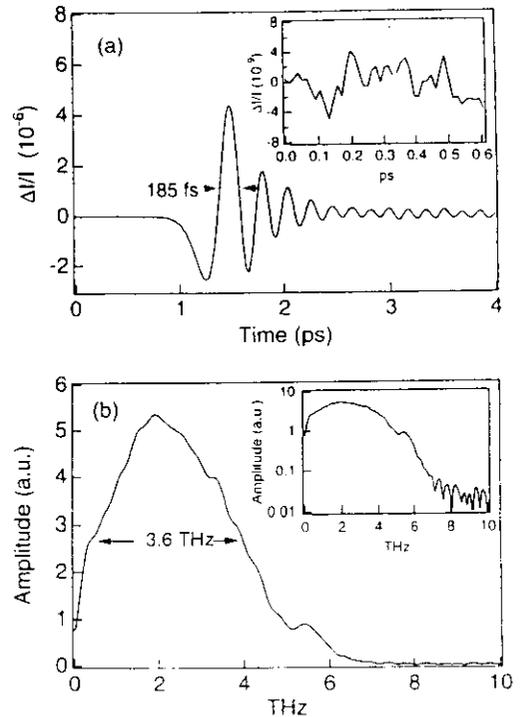
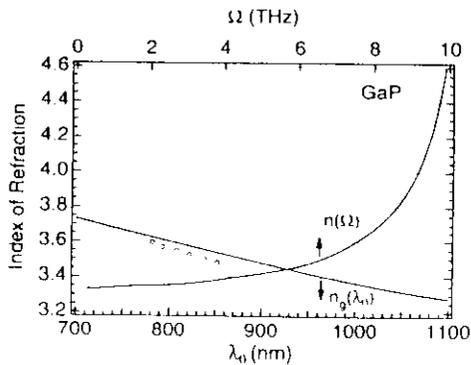


Optical rectification

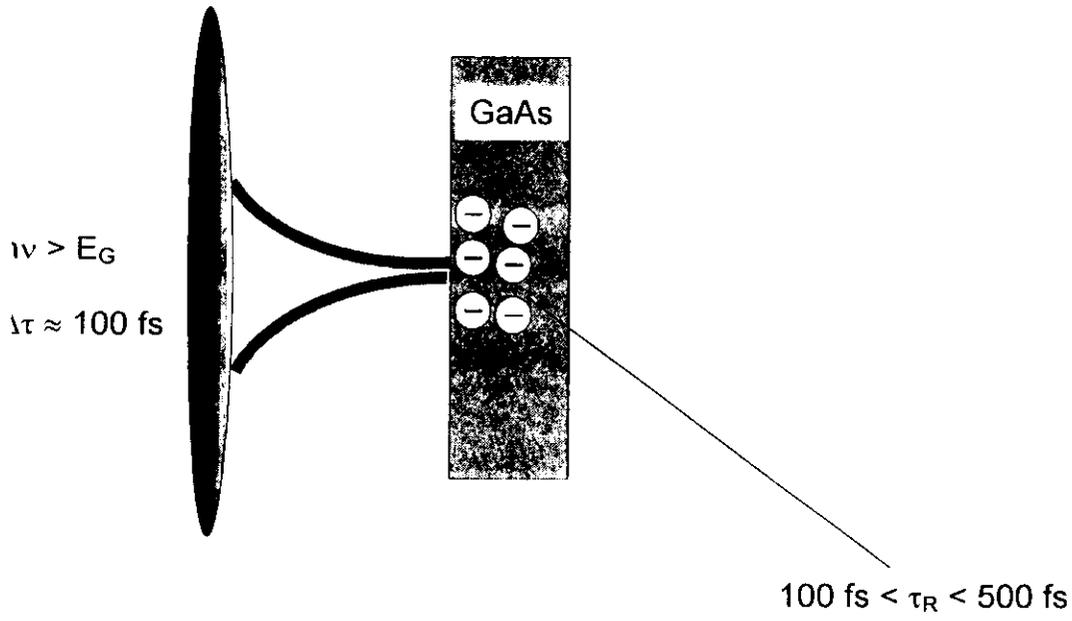
- o Nonlinear polarization $P_{NL}(t) \propto I_{opt}(t)$
- o Voltage $U(t) \propto \frac{dI_{opt}}{dt}(t)$
- o Bandwidth of fs-pulse determines bandwidth of THz pulse
- o GVM limits crystal length
- o Nonlinear materials
 - o GaAs
 - o LiNbO₃
 - o poled polymeres



Optical rectification



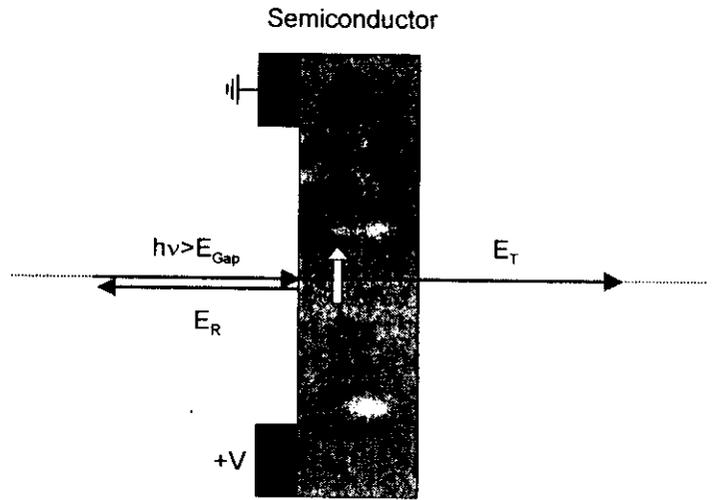
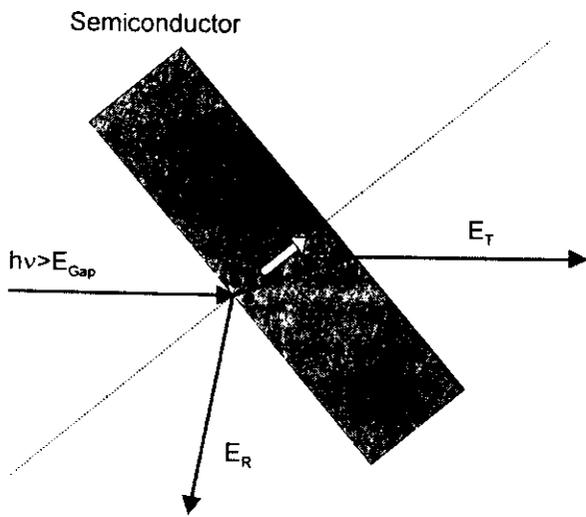
Transient Photoconductivity



Transient photoconductivity I

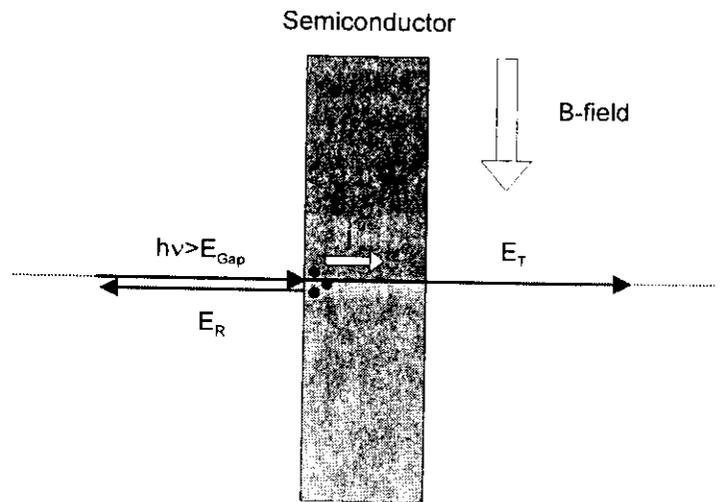
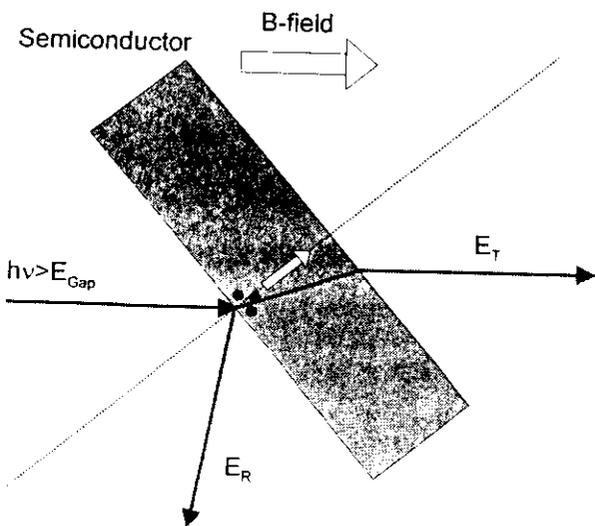
Surface depletion field

external E-field

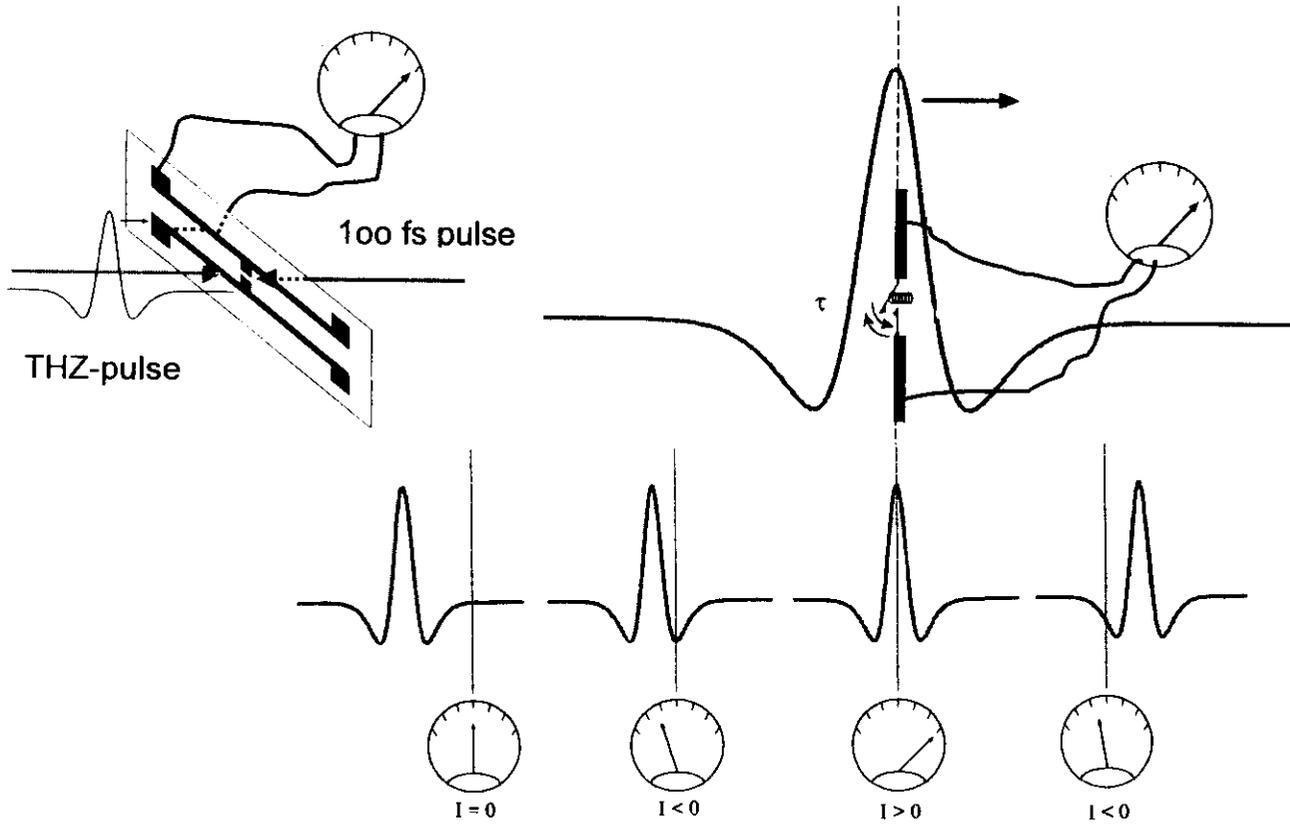


Transient photoconductivity II

Magnetic field



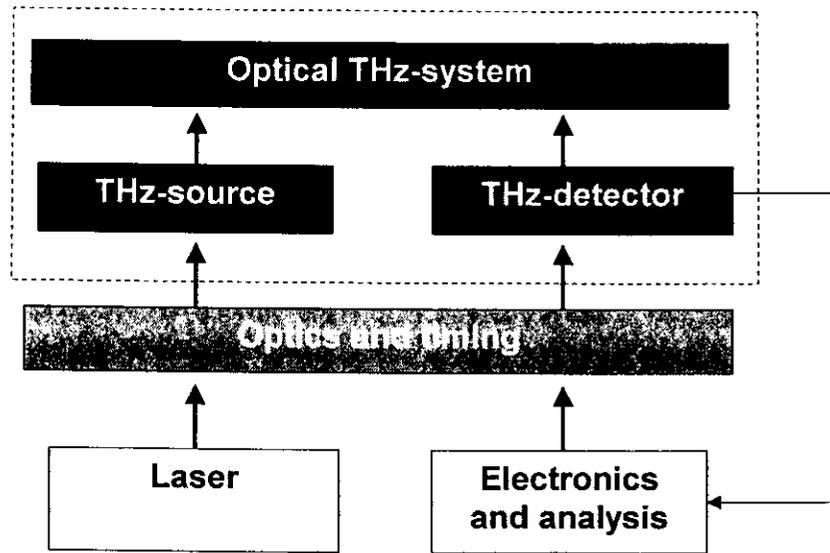
Coherent detection of fs-THz-pulses



THz-system

4 components:

- Laser and optics (100 fs Laser, opt. delay line beam path)
- THz-source and detector (photoconductive switches, THz-optics)
- THz-optics (refl./transm. optics)
- Electronics



Pump source

Requirements

- o Pulse length $\Delta\tau < 100$ fs
- o Average power $P_{av} = 10 \dots 20$ mW
- o Repetition rate $\nu_{rep} = 50 \dots 200$ MHz
- o Wavelength $\lambda = 600 \dots 800$ nm
- o Diode laser based

⇒ Diode laser pumped solid state laser

Generation of ultrashort pulses

Problems of mode-locked lasers with pulse lengths below 100 fs:

Type of mode-locking

- passive mode-locking
- self starting
- low pump power

How to manage dispersion

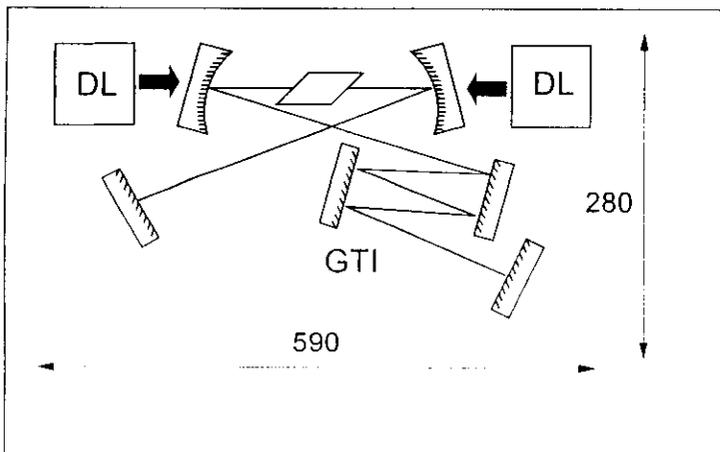
- Compensation of GVD
- high order dispersion
- phase control

KLM
 saturable absorber
 nonlinear mirror

prisms
 GTI-mirrors
 mirrors with chirp

Compact fs sources

- o Kerr-Lens-Modelocking (*no additional elements in the resonator*)
- o Saturable semiconductor absorbers (*self starting, compact*)
- o Optimization of the pump source (*minimum requirements for pump optics*)
- o GVD compensation with mirrors (*compact set-up*)



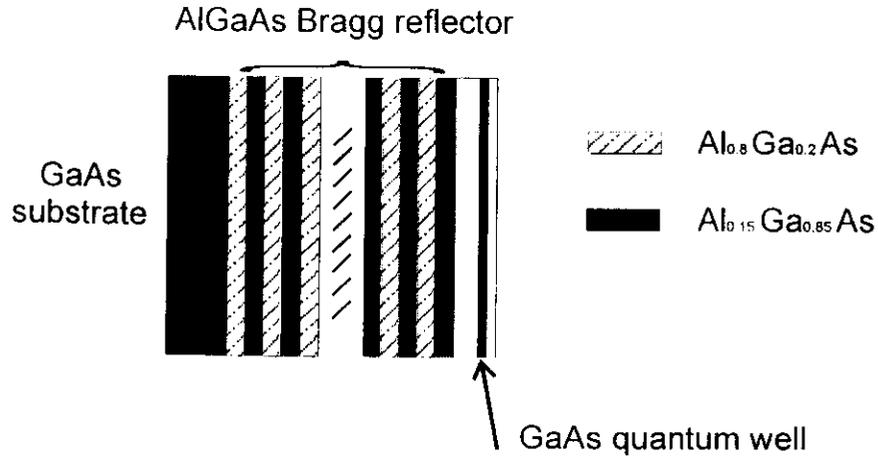
- o Dimensions: 10" x 20"
- o Price: Components < \$ 10.000,-

Expected results:

- o Output power > 100 mW
- o puls lengths < 100 fs
- o and repetition rates > 250 MHz

Saturable absorber

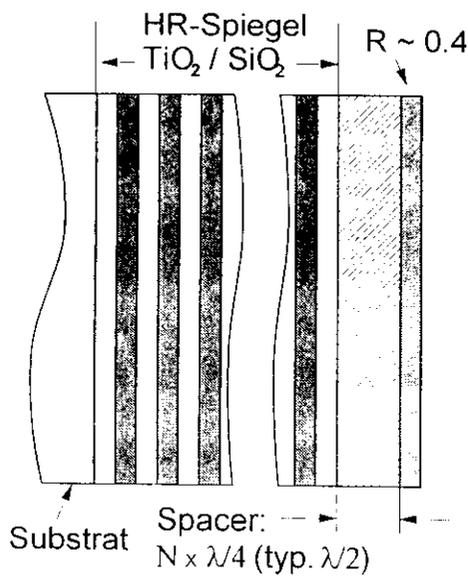
- o Saturable Bragg reflector "SBR"



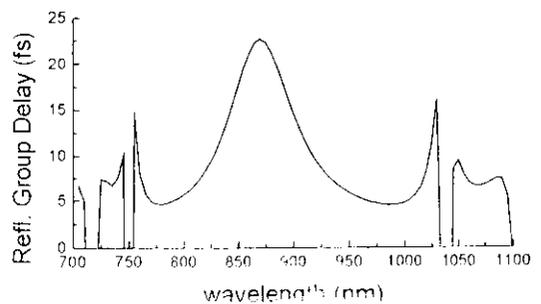
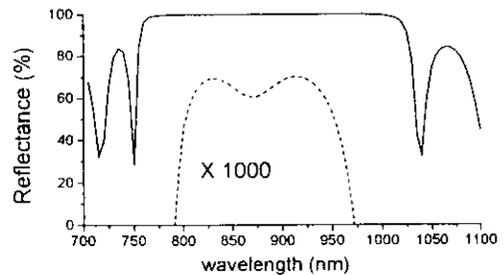
⇒ Fast saturable absorber + soliton mode-locking ⇐

„Gires-Tournois-interferometer-mirror (GTI)

- o Mirror with "integrated etalon"

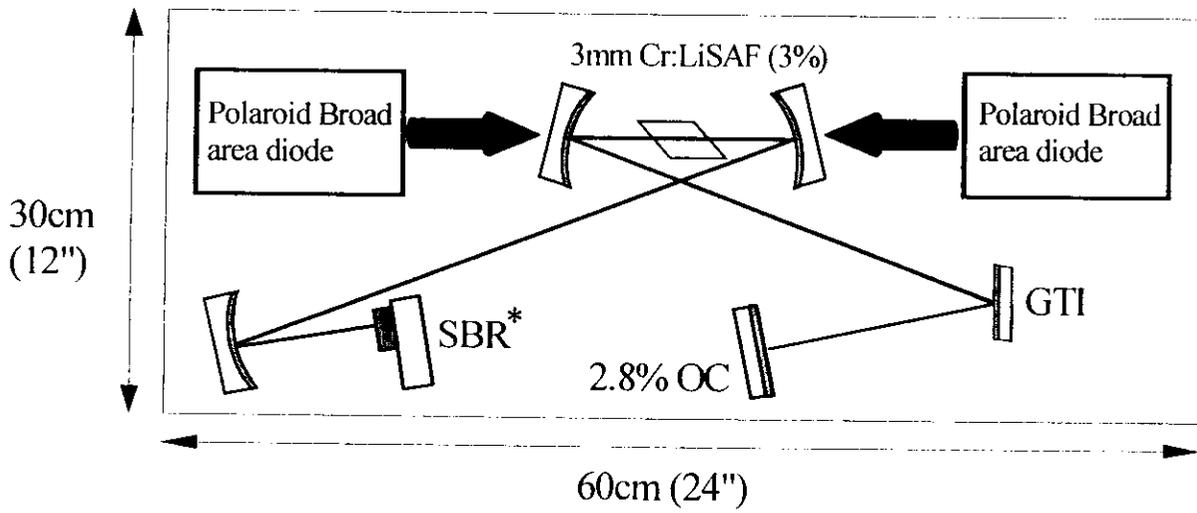


- o Transmission and phase retardation



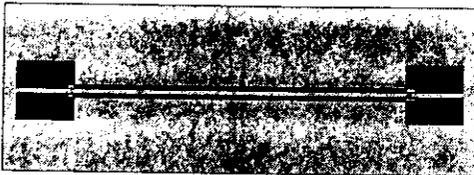
Fs Cr:LiSAF Laser

- o Typical performance: $P_{av} > 65 \text{ mW}$
 $\Delta\tau < 100 \text{ fs}$
 $\nu_{rep} > 100 \text{ MHz}$



THz-source and -detector

THz-source



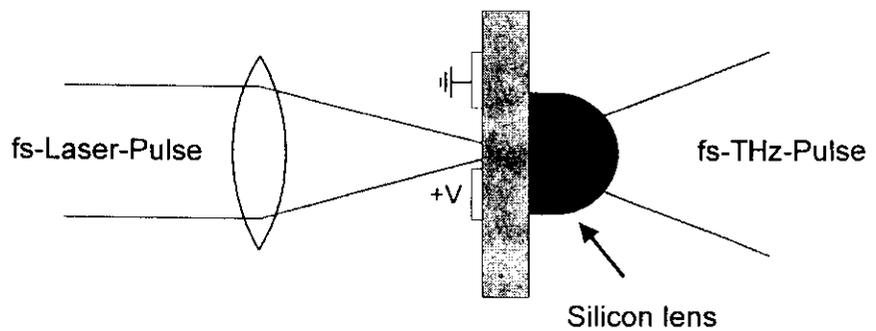
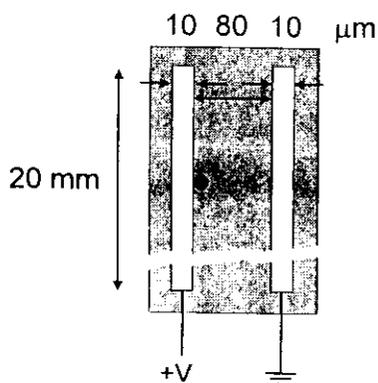
- o GaAs, $R > 10^6 \Omega \cdot \text{cm}$
- o 10 mW damage threshold
- o voltage: 100 V
- o fragile

THZ-detector



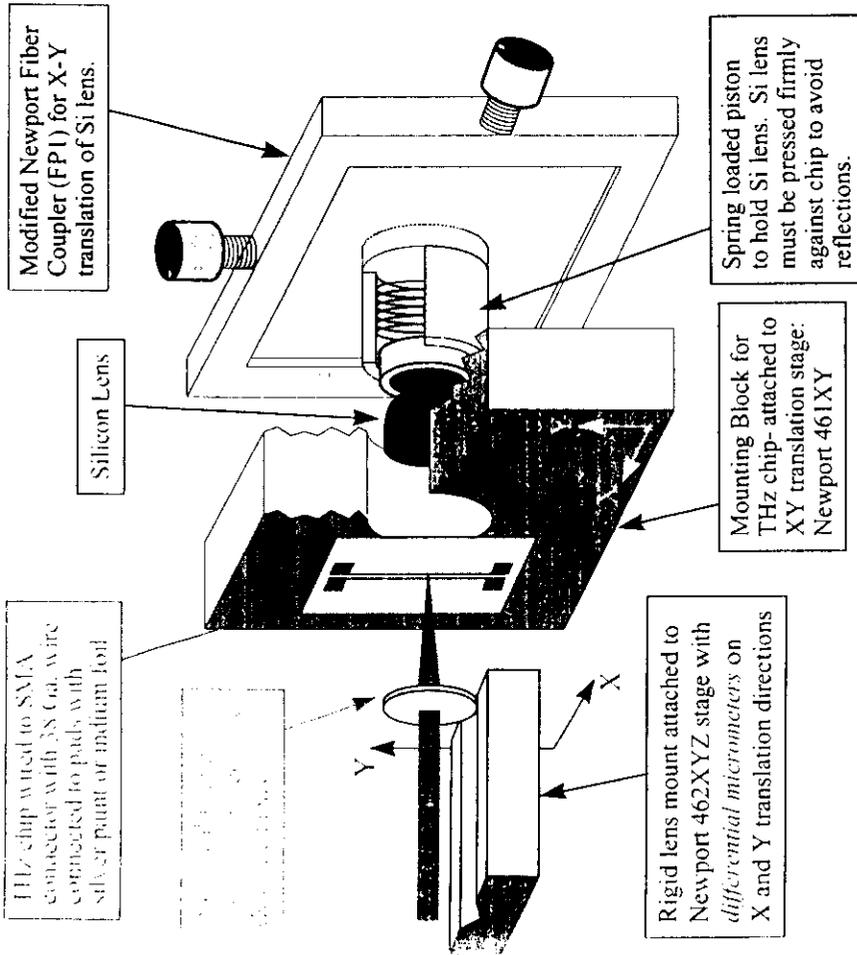
- o Silicon (on sapphire)
- o 100 mW damage threshold
- o voltage: 10 V (5 μm gap)
- o mechanically stable

GaAs - Transmitter



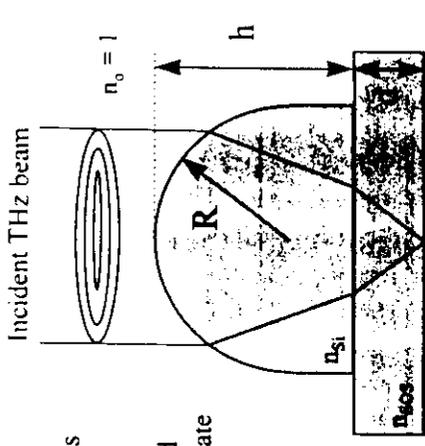
- o specific resistance $> 1 \text{ M}\Omega \text{ cm}$
- o average IR power $< 10 \text{ mW}$
- o bias voltage $< 100 \text{ V}$
- o fragile !!

THz-chip set-up



- Mechanical rigidity paramount- need to focus laser on to 5 μm gap.
- Mount for source and detector are identical.

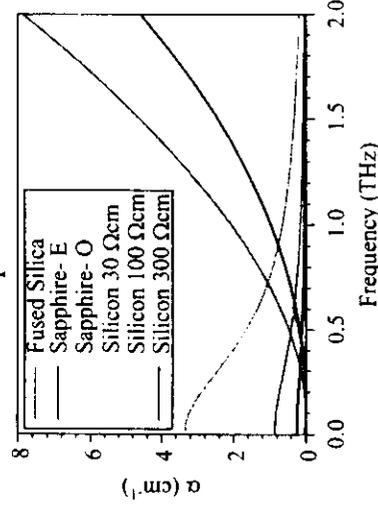
THz-optics



- Use of high resistivity Si for lenses gives best performance.
- Silicon Lens on back of source and detector collimates THz beam: estimate lens thickness from ray optics.

$$h = \frac{n_{Si} R}{n_{Si} - n_o} - d \frac{n_{Si}}{n_{Si}}$$

Transmissive Optics:

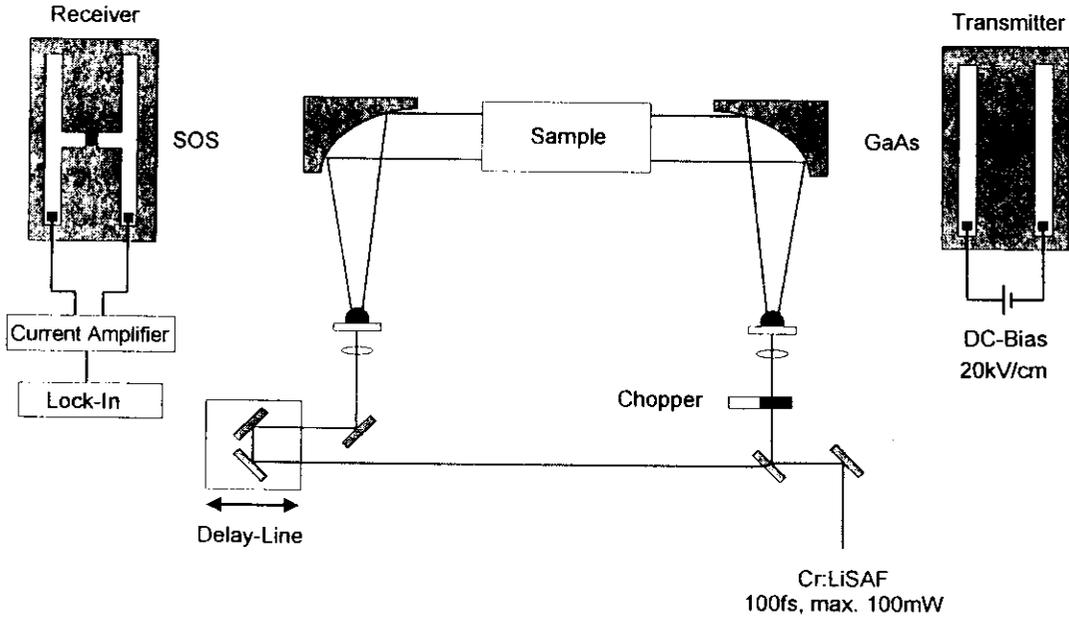


	n	T ₁	R ₁	T ₂	R ₂	T _{total}
Fused Silica	1.95	0.68	-0.32	1.32	0.32	0.90
Sapphire- Ordinary	3.07	0.49	-0.51	1.51	0.51	0.74
Sapphire- Extraordinary	3.41	0.45	-0.54	1.55	0.55	0.70
Silicon > 100 Ωcm	3.42	0.45	-0.55	1.55	0.55	0.70

1) D. Grischkowsky, S. Keiding, M. van Exter, Ch. Fattinger, JOSA B, vol. 7, p. 2006, 1990.

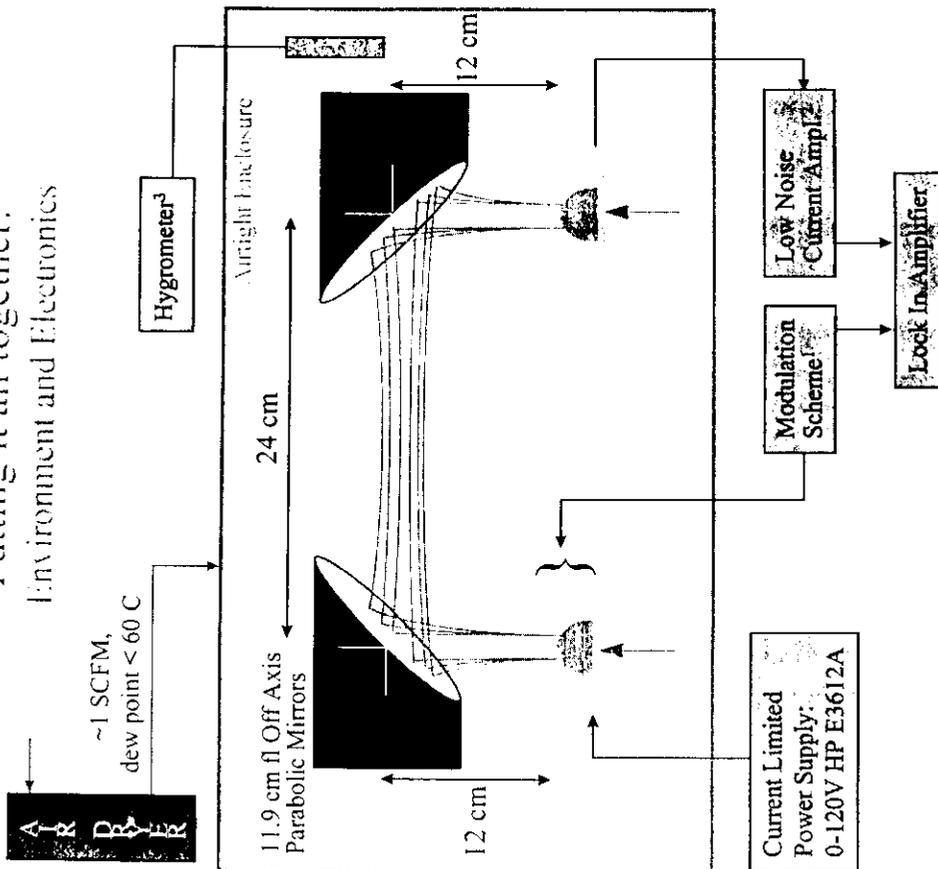
THz set-up

- o Photoconductive switches using Silicon (receiver) and GaAs (transmitter)



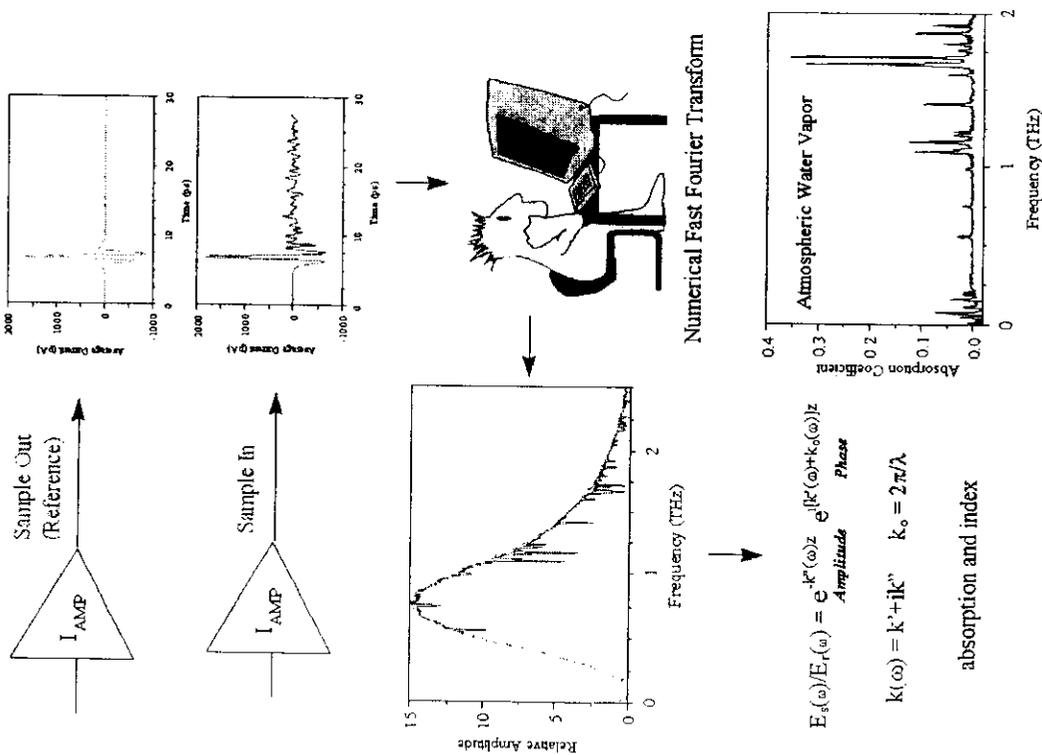
THz set-up

Putting it all together:
Environment and Electronics



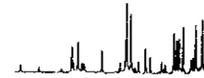
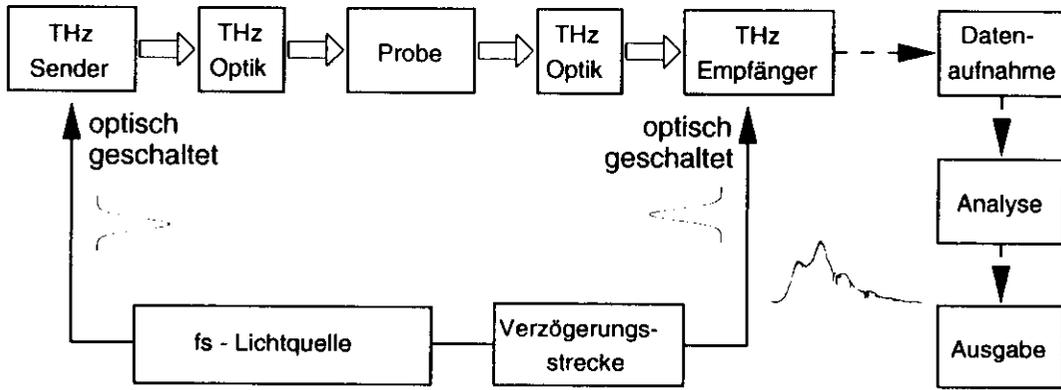
- 1) Modulation can be mechanical chopping of laser beam, THz beam*, or modulation of voltage bias on source (* generally best results).
- 2) Ilthaco model 1211, Stanford Research Systems model SR570 for example.
- 3) Hygrometers capable of measuring dewpoints to -20 C (100 ppm) are available from a wide variety of suppliers such as Omega or Fisher Scientific. Shaw (UK) sells a "Super Dew" model capable of measuring to -110 C (ppb range).
- 4) Air dryers are available from Balston or less expensively from Great Lakes Air and Airtek

Time Domain Spectroscopy



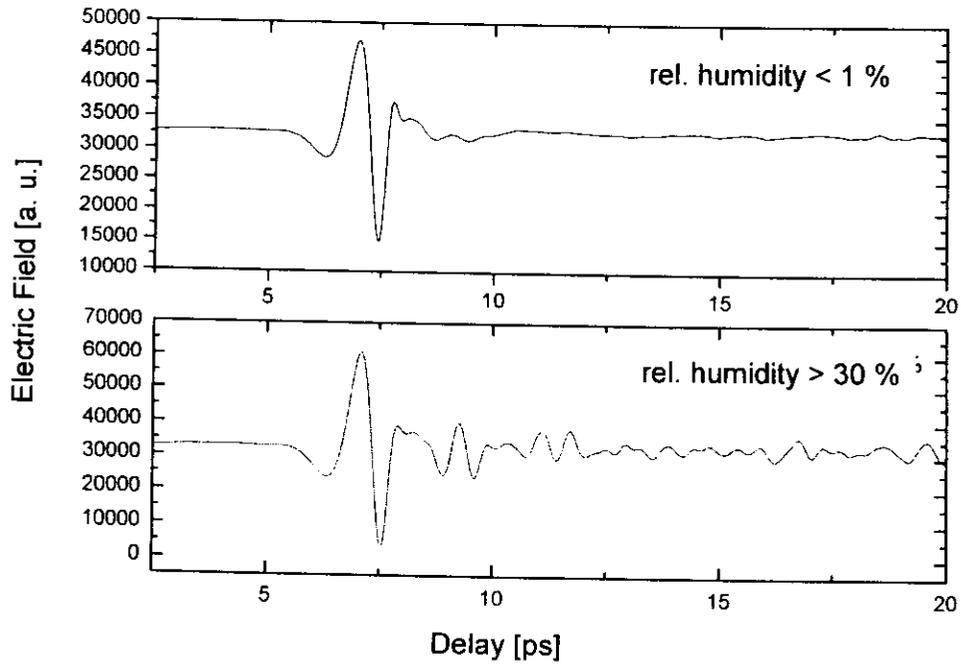
(<http://bubba.ucc.okstate.edu/elec-engr/research/cir/thzopto/bsuclid.html>)

THz-system



fs-THz-pulses

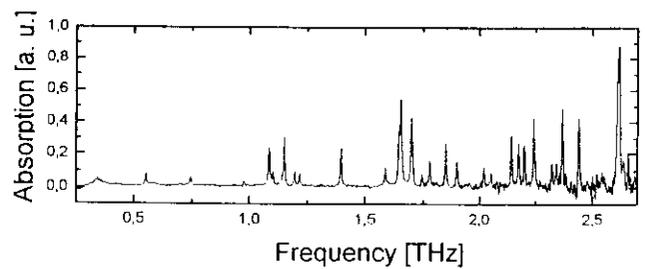
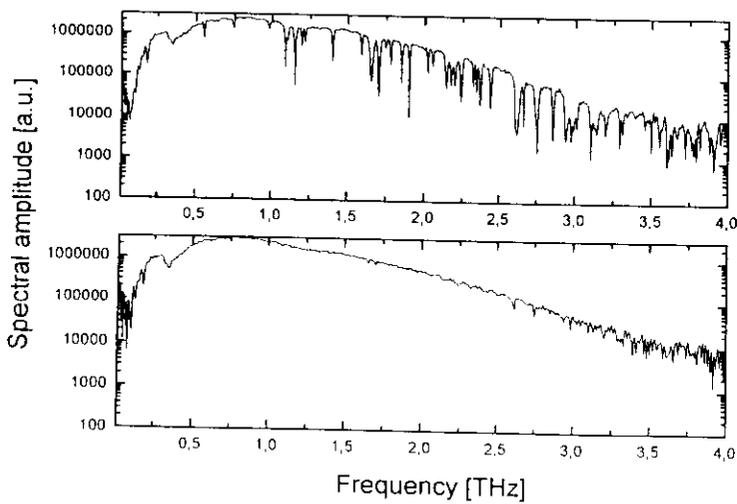
⇒ Dispersion changes the time structure of the pulse:



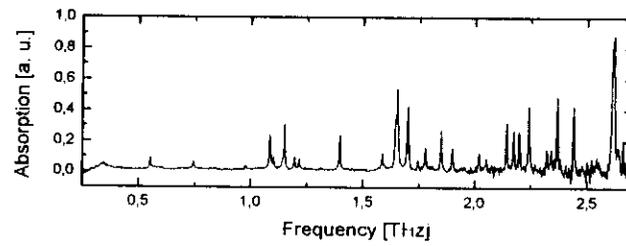
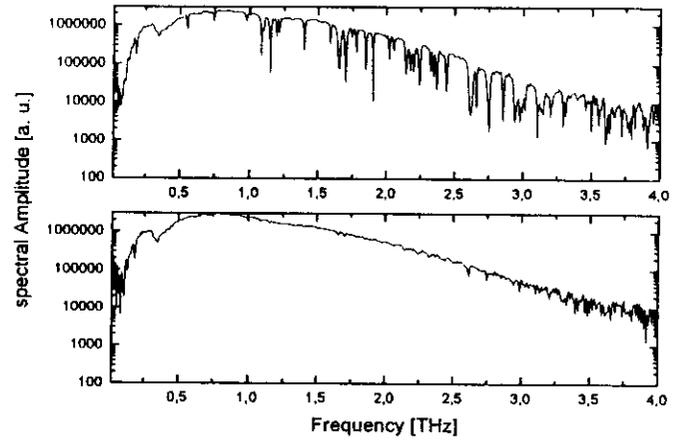
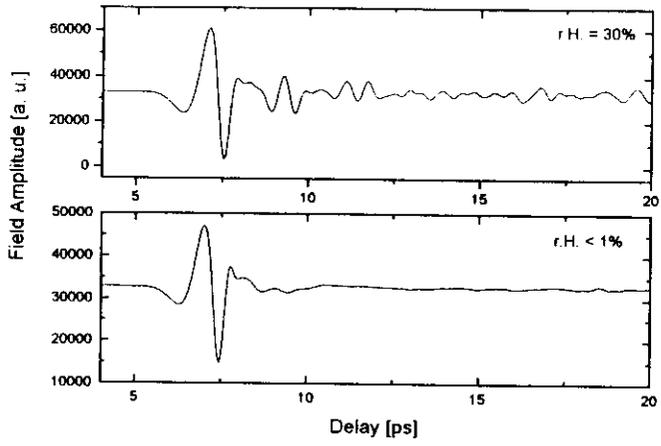
Bandwidth

o Transmitter: GaAs

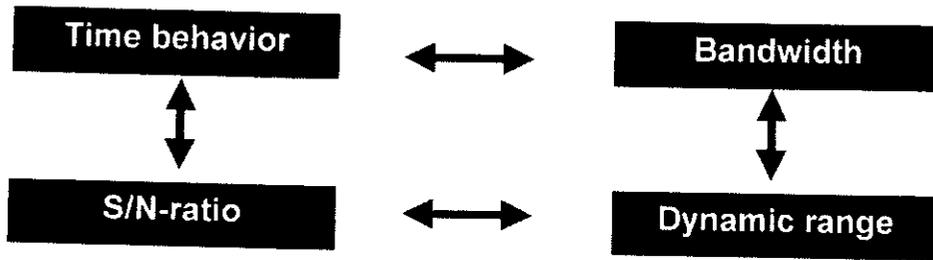
o Receiver: SOS



THz-TDS on Water Vapor



Properties of THz sources



o Bandwidth: Large dipole: \Rightarrow small bandwidth
maximum at low frequencies

limited by: optics, material, adjustment,
recombination time

Dipole	10 % Bandwidth	50 % Bandwidth	Maximum
200 μm	0,05 – 0,81	0,09 – 0,31	0,21
50 μm	0,08 – 2,0	0,27 – 1,2	0,60
30 μm	0,08 – 2,6	0,31 – 1,6	1,0
10 μm	0,11 – 3,2	0,52 – 2,0	1,0

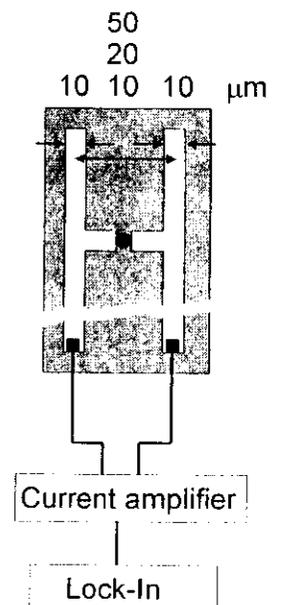
THz-receiver using photoconductive switches

- o Silicon on sapphire (SOS)
- o antenna structure made of aluminum

Bandwidth



Length of Dipole [μm]	10% Bandwidth [THz]		50% Bandwidth [THz]		Maximum [THz]
50	0,08	2,0	0,27	1,2	0,6
30	0,08	2,6	0,31	1,6	1,0
10	0,11	3,2	0,52	2,0	1,0



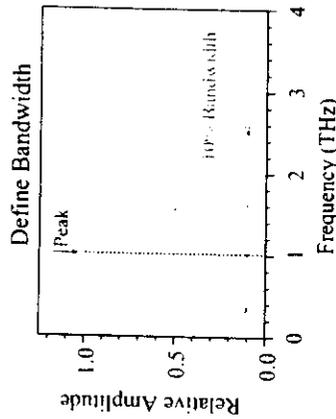
Signal-to-noise-ratio:

$$1000:1 < S/N < 10000:1$$

$$I_N \approx \frac{I}{\sqrt{Z_{chip}}}$$

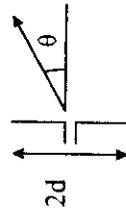
Bandwidth considerations

Bandwidth: Larger dipoles have smaller bandwidth peaked at lower frequencies. Bandwidth is limited by the optics, material absorption, misalignment, and ultimately semiconductor response time.



“Typical” Values in THz

Dipole	10% BW	50% BW	Peak
200 μm	.05 to .81	.09 to .31	.21
50 μm	.08 to 2.0	.27 to 1.2	.60
30 μm	.08 to 2.6	.31 to 1.6	1.0
10 μm	.11 to 3.2	.52 to 2.0	1.0

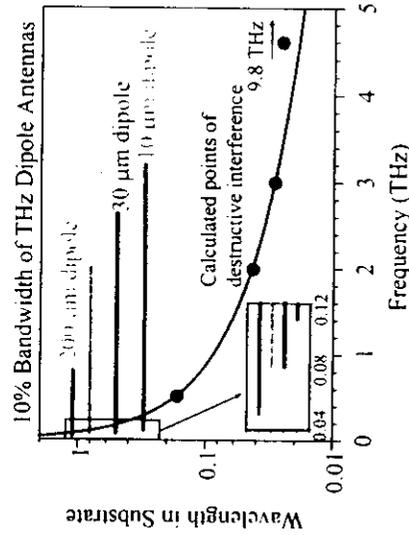


Hertzian Dipole: $d \ll \lambda$

$$E_{rad} \propto \frac{d}{\lambda}$$

Dipole: $d \sim \lambda$, interference along length of dipole.

$$E(\theta) \approx \left[\frac{\cos(kl \cos\theta) - \cos kl}{\sin\theta} \right]$$



Spectral bandwidth

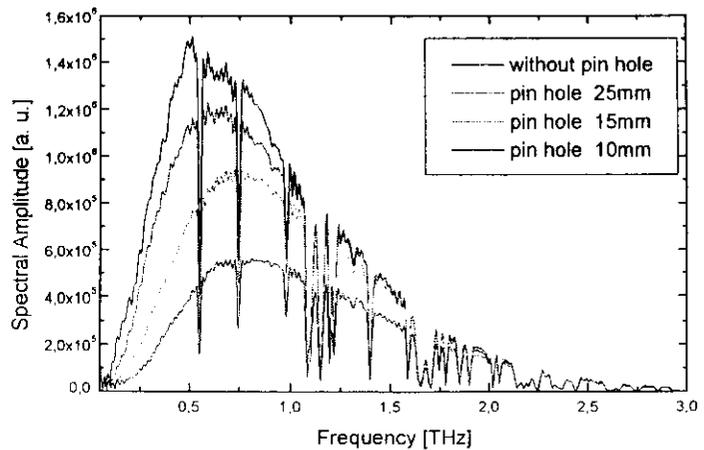
o Point source ($\varnothing \approx 20 \mu\text{m}$) \Rightarrow diffraction



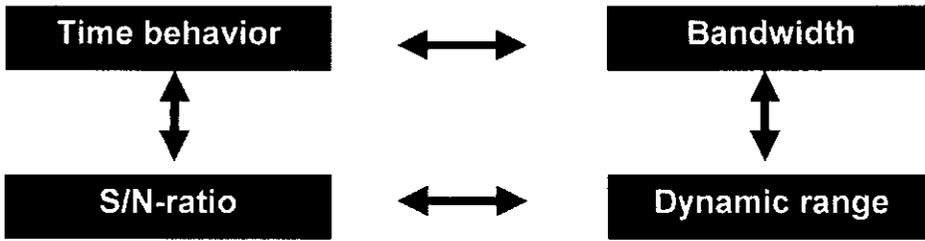
o Radial frequency distribution



- low frequency components at the boundary of the THz beam
- high frequency components inside the beam



Properties of THz sources



- o S/N-range: Large dipole \Rightarrow large S/N
 $1\,000 : 1 < S/N < 10\,000 : 1$

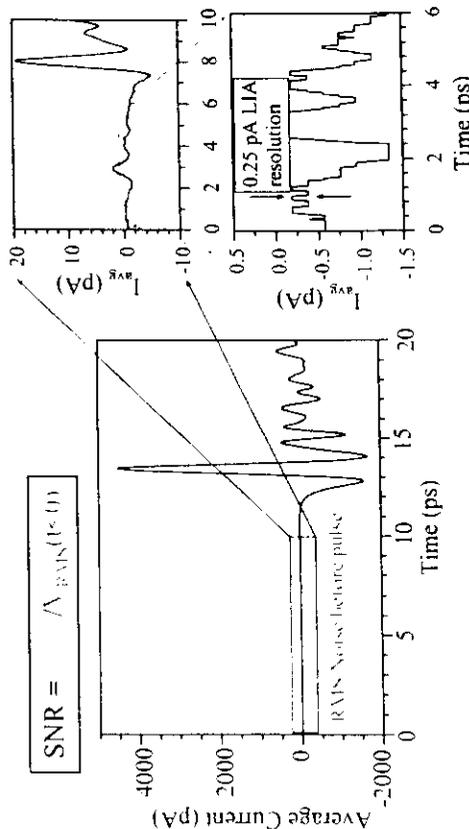
$$S/N = \frac{V_{\text{peak}}}{V_{\text{rms}}(t < 0)}$$

- o Noise sources: Impedance of the detector $I_{\text{noise}} \approx \frac{1}{\sqrt{Z_{\text{chip}}}}$

Laser-noise (dominant for $P > 10\text{ mW}$)

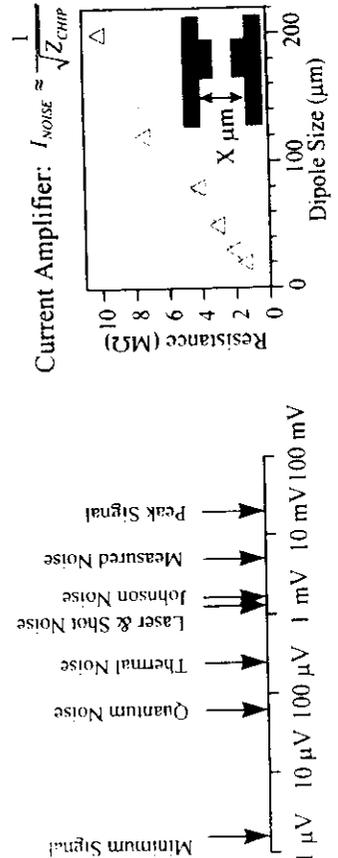
S/N Ratio

S/N Ratio: The dynamic range generally increases with dipole size. $S/N < 1000:1$ is poor while $S/N > 10,000:1$ is very good. The noise floor is most dependent on the impedance of the detector and laser noise while the peak signal depends on the same factors as the bandwidth.



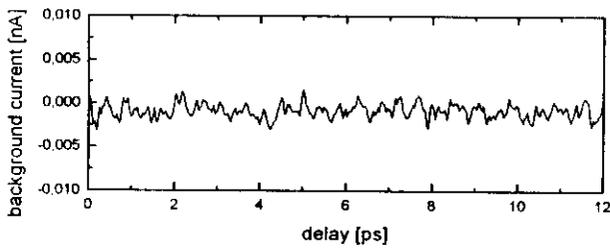
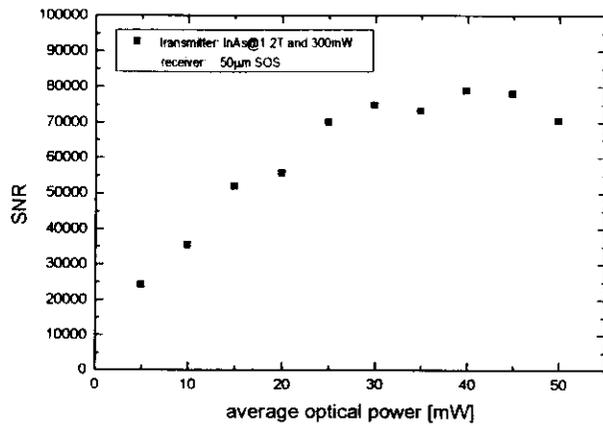
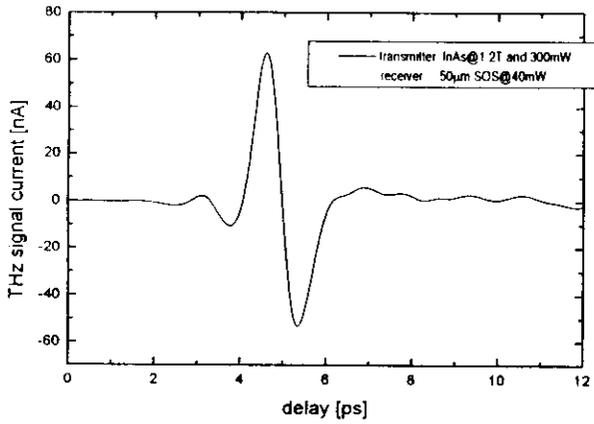
Dominant Noise vs. Power of Optical Beam

- High ($> \sim 10\text{ mW}$): Laser Noise
- Low ($< \sim 10\text{ mW}$): Noise due to Z_{chip}



Lockin Resolution: at best 16 bits (1:65,536), as low as 14 bits (1:16,384)

Signal to Noise

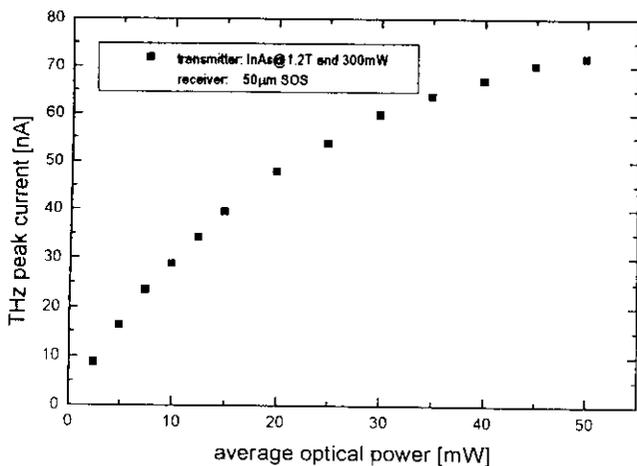


- o Signal to Noise: ~ 80000
(30ms Lock-In time constant)

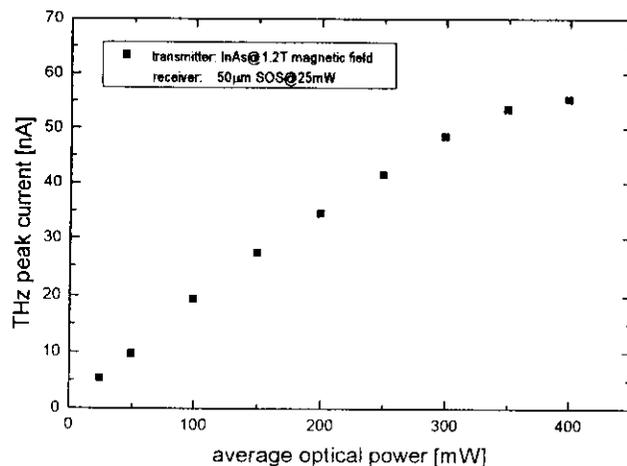
Characterization of THz Receiver and Emitter

Dependence of peak THz signal current on applied infrared power:

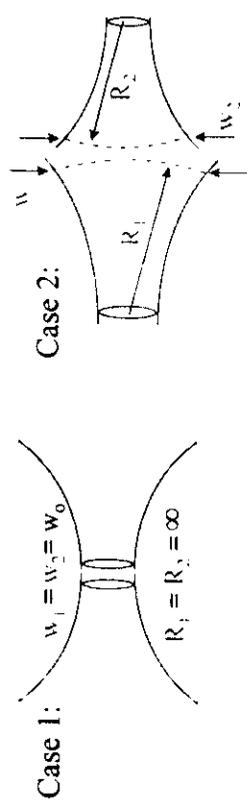
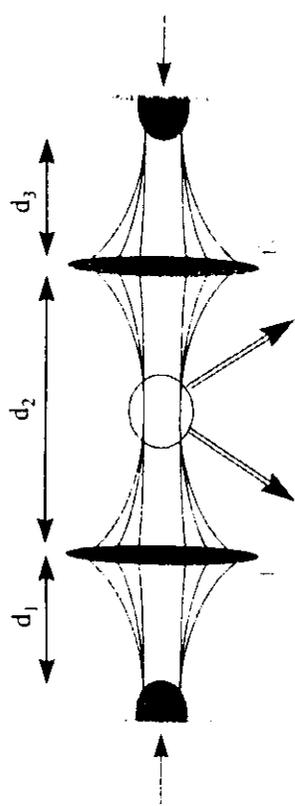
receiver chip (SOS)



transmitter (bulk InAs)



THz beam waist considerations



Good transmission efficiency achieved by matching beam waists at some point in system. Assume Gaussian beam with waist at Si lens!

Case 1: Waists match- good coupling. $w_1 = w_2$; $R_1 = R_2 = \infty$

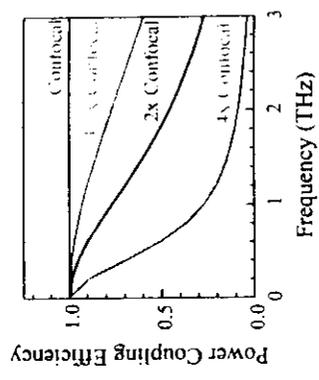
Case 2: Mismatch of beams- poor coupling. $w_1 \neq w_2$; $R_1 \neq R_2$

Power Coupling Efficiency², C:

$$C = \frac{4}{\left(\frac{w_1}{w_2} + \frac{w_2}{w_1}\right)^2 + \left(\frac{\pi}{\lambda} \frac{w_1 w_2}{R_2 - R_1}\right)^2}$$

Optimal coupling is confocal configuration:

$$d_1 = f_1 = d_3 = f_2, d_2 = 2f$$



1) P. Uhd Jepsen, S. R. Keiding, Opt. Lett., vol. 20, p. 807, 1995.

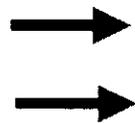
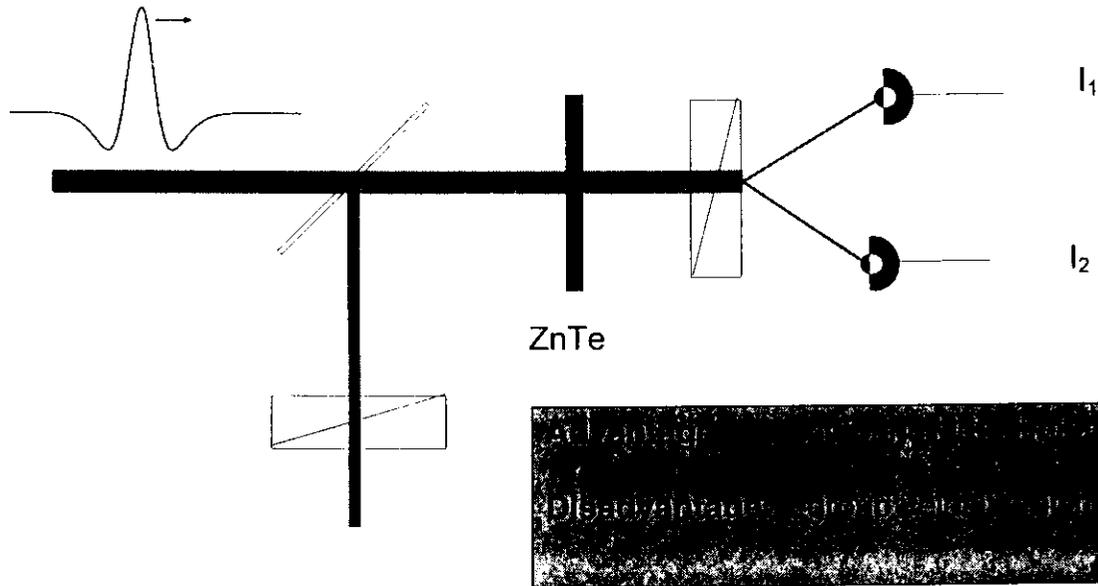
2) J. C. G. LeSurf, Millimetre-wave Optics, Devices, and Systems, Adam Hilger, New York, 1990

„THz-source“

Properties of the fs-THz-source:

- o **Pulsed** source ($\Delta\tau \approx 1$ ps) with **high repetition rate** (50 ... 100 MHz)
- o **Broadband** THz-radiation
$$30 \text{ GHz} < \nu < 30 \text{ THz}$$
- o High S/N-ratio
- o Noise reduction by **coherent** detection and "**optical gating**" ("duty cycle" $\approx 5 \cdot 10^{-4}$)
- o **Collimated and directed** THz-radiation (point source)
- o **Diode laser based** THz-source

Electro-optical sampling



extremely thin crystals

small S/N-ratio

Electro-optical detection using GaP and ZnTe

GaP

(X.-C. Zhang et al.)

ZnTe

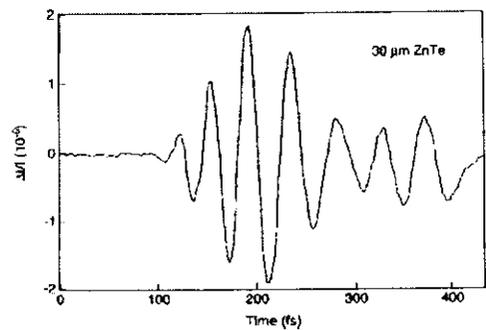
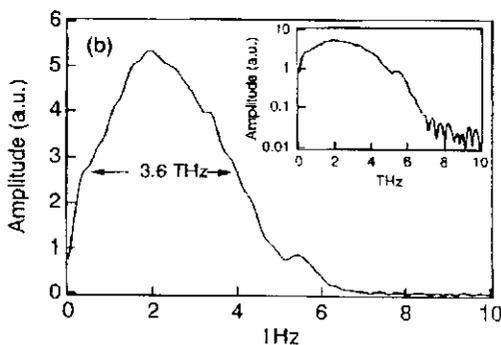
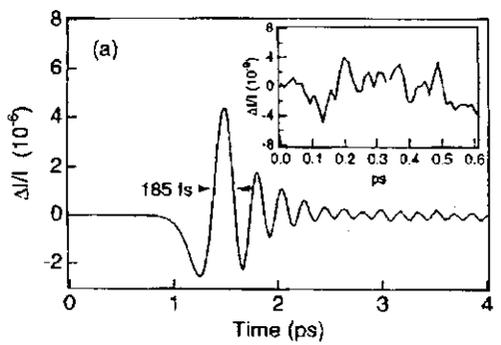


FIG. 2. Temporal waveform of the THz radiation measured by a 30 μm ZnTe sensor. The shortest oscillation period is 31 fs.

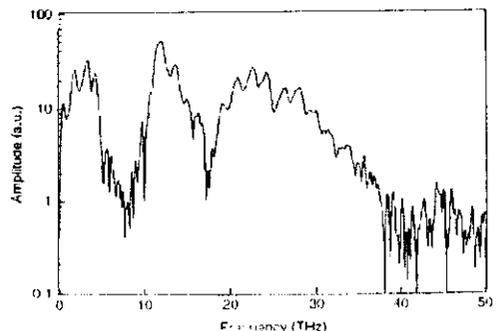
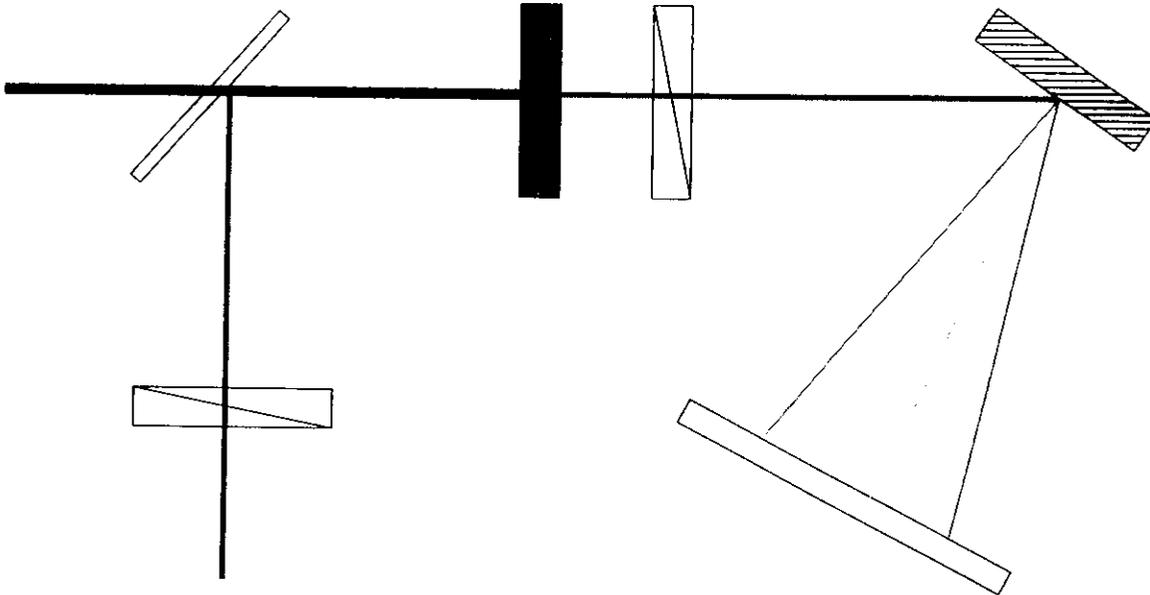


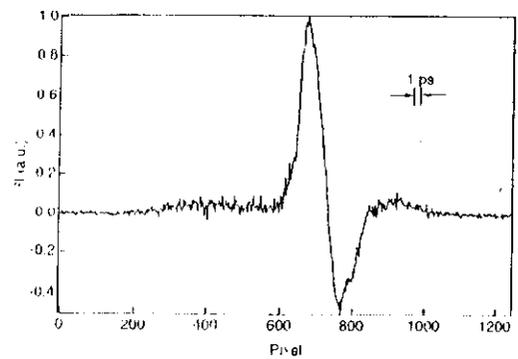
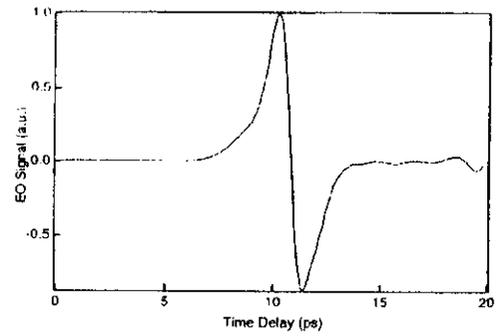
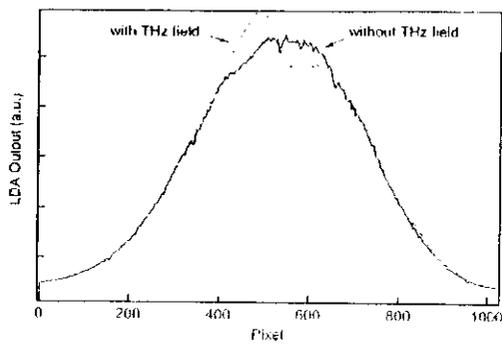
FIG. 1. (a) Temporal waveform of THz radiation measured with a 180 μm GaP sensor. The shortest oscillation period is 185 fs. (b) Frequency spectrum of the THz radiation measured with a 180 μm GaP sensor. The peak frequency is 3.6 THz.

„Single-Shot“ Electro-optical sampling

X.-C. Zhang et al.



„Single-Shot“ Electro-optical sampling



Here is a list of other groups involved in THz-TDS. Some are directly involved in advanced instrument development and characterization, while others are using it strictly as a source for far-infrared spectroscopy. This is a partial list, in no particular order. It is taken from Dan Mittleman's home page

(<http://www.ece.rice.edu/~daniel/Mittleman.html>).

There are direct links to the groups listed below on his home page. It is worth while to visit this home page.

Martin Nuss, Bell Labs, Lucent Technologies
Igal Brener, Bell Labs, Lucent Technologies
Xi-Cheng Zhang, RPI
A number of people at the CUOS, University of Michigan, including **Phil Bucksbaum, Ted Norris, and John Whitaker.**
Jeff Bokor, University of California, Berkeley
Joe Orenstein, University of California, Berkeley
Tony Heinz, Columbia University
Brian Kolner, UC Davis
Frank Hegmann, Univ. of Alberta
Center for Terahertz Science and Technology, UCSB
Dan Grischkowsky, Oklahoma State University has an interactive THz lab tour!
John Federici, NJIT
Andy Weiner, Purdue University
Norbert Scherer, University of Chicago
Robin Hochstrasser, University of Pennsylvania
Stephen Ralph, Georgia Tech (nascent web page)
Dan van der Weide, Delaware
Beth Parks, Colgate University
Ultrafast Optoelectronics Lab, Univ. of Maryland
Picometrix, Inc.
Molecular Optoelectronics Corporation
Toni Taylor, Los Alamos
Ted Heilweil, NIST Gaithersburg
Charles Schmittenmaer, Yale University
Shun Lien Chuang, U. of Illinois, Urbana
Bob Guenther, Duke University
Elliot Brown, DARPA Electronics Technology Office
S. R. Andrews, Bath University, UK
Dan Some, Weizmann Institute
Frank De Lucia, Microwave Laboratory, Ohio State University
Hermann Harde, Hamburg
Jochen Feldmann, Munich
Martin Koch, Braunschweig
Martin Wegener, Karlsruhe
Rene Beigang, Kaiserslautern, in German
Heinrich Kurz and Peter Haring Bolivar, Aachen
Karl Unterrainer, University of Innsbruck
Hartmut Roskos, Frankfurt
Søren Keiding, Aarhus, Denmark
Jurgen Kuhl, Max-Planck Institute, Stuttgart
Ingrid Wilke, University of Hamburg
Hanspeter Helm, University of Freiburg
Klaas Wynne, Femtosecond Research Ctr., Strathclyde UK, as well as
GODOT, a European consortium of THz groups.
ENSTA, Palaiseau, France (does the English version work yet?)
M. Tani, Kansai Research Center, Kobe, Japan
Institute of Solid State Electronics, Technical University of Vienna
Jean-Louis Coutaz, University of Savoy, France
JoungHo Kim, Korea Advanced Institute of Science and Technology