THz Time-Domain Spectroscopies and Applications

Ci-Ling Pan 潘犀靈
Department of Physics
National Tsing Hua University
Hsinchu, Taiwan 30013, ROC

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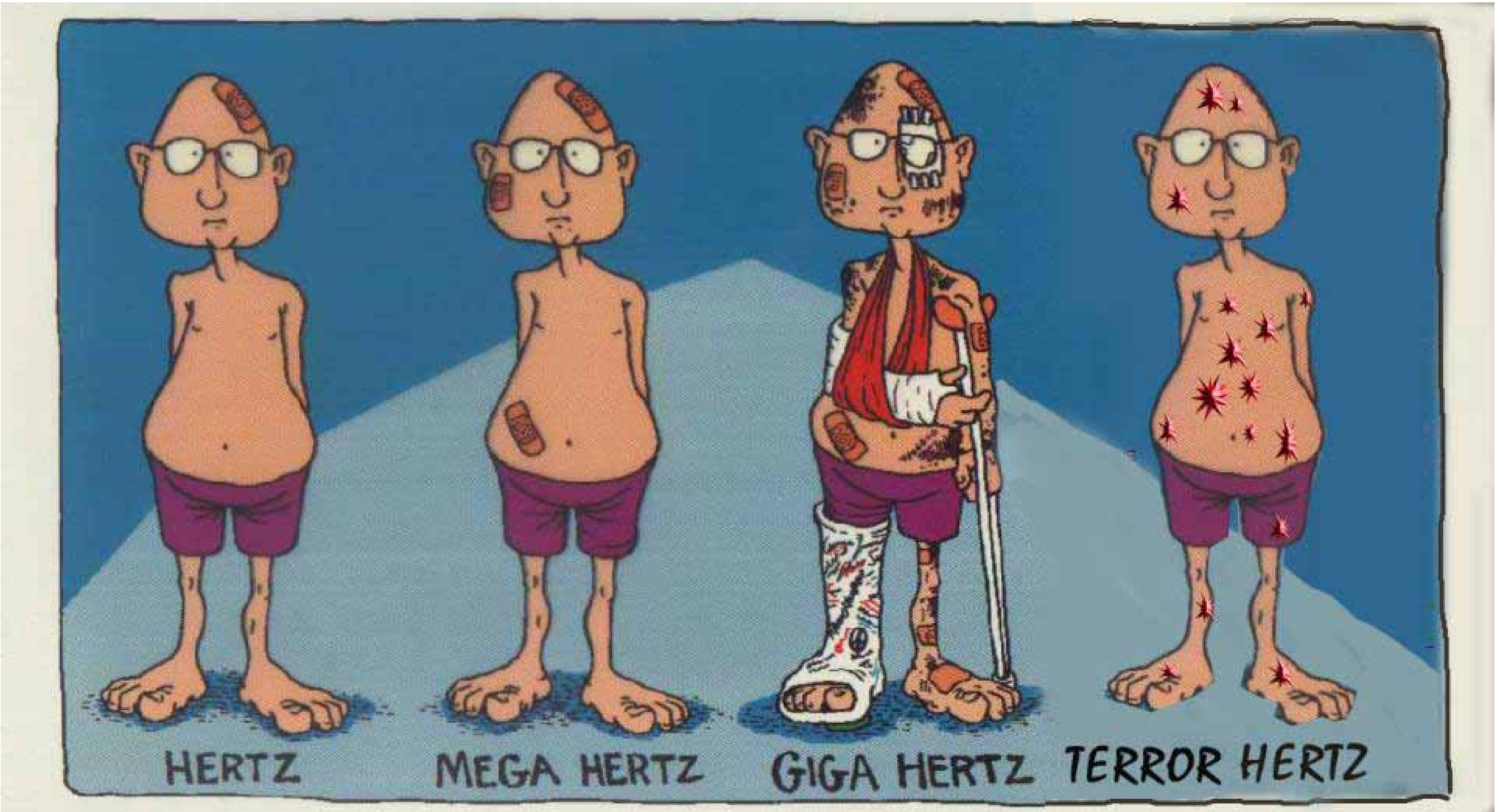
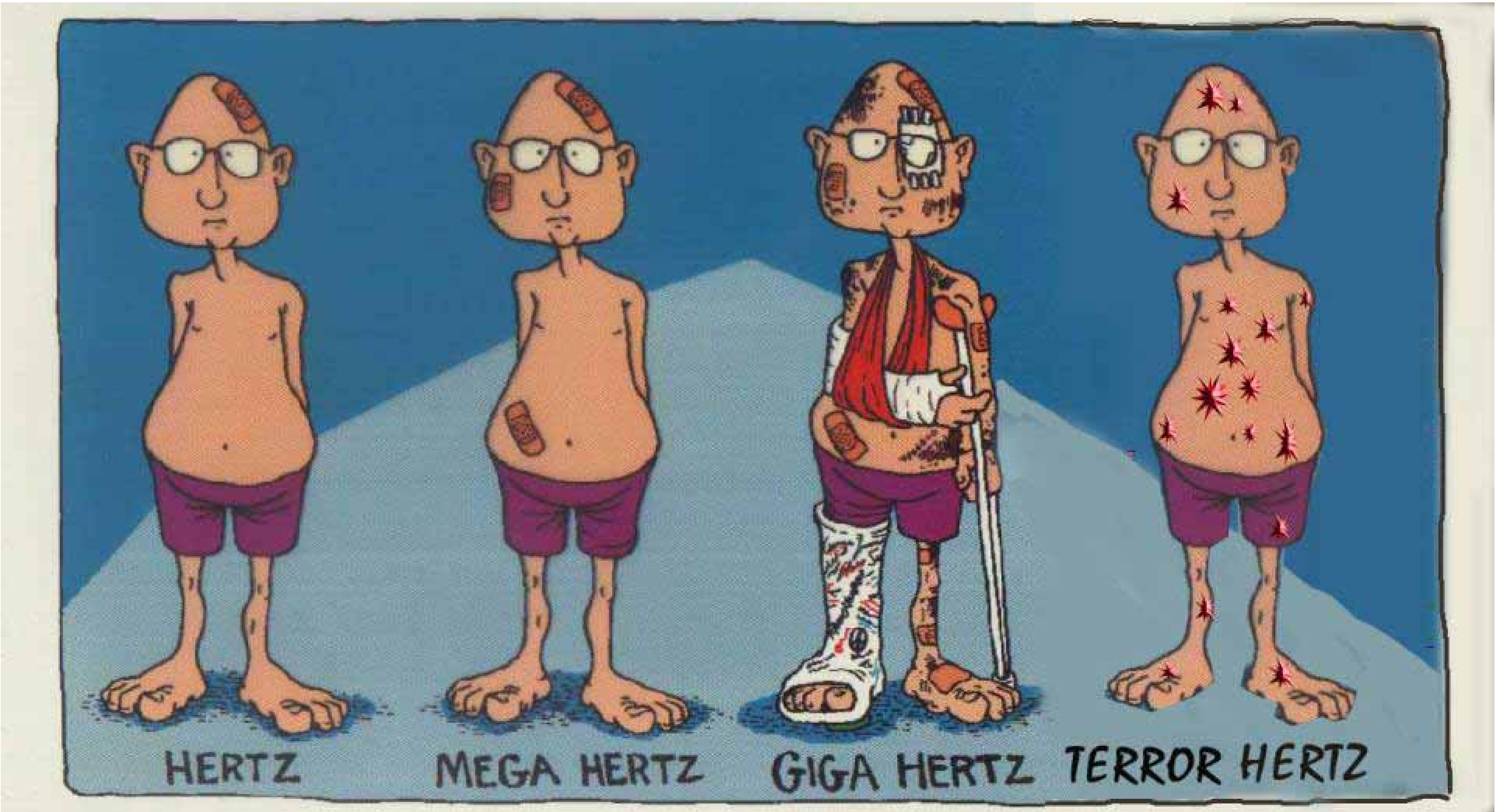
Outline

- Time-Gated or Time-Resolved Measurements: Basics
- THz basics
- THz Spectroscopy (THz-TDS)
- Examples of THz-TDS: Extraction of Optical Constants of Materials
- Towards THz Wireless Communications.

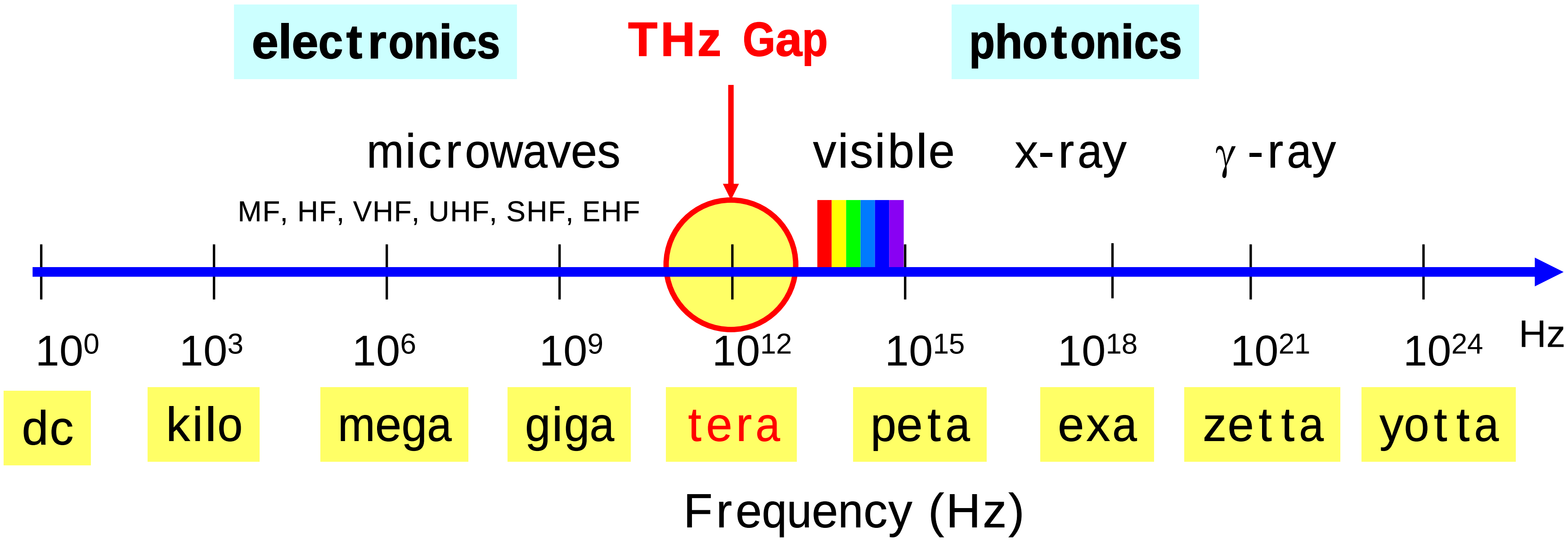

HERTZ
MEGA HERTZ
GIGA HERTZ
TERROR HERTZ



Hertz = Hurts

T-Ray: Frontier in Science and Technology

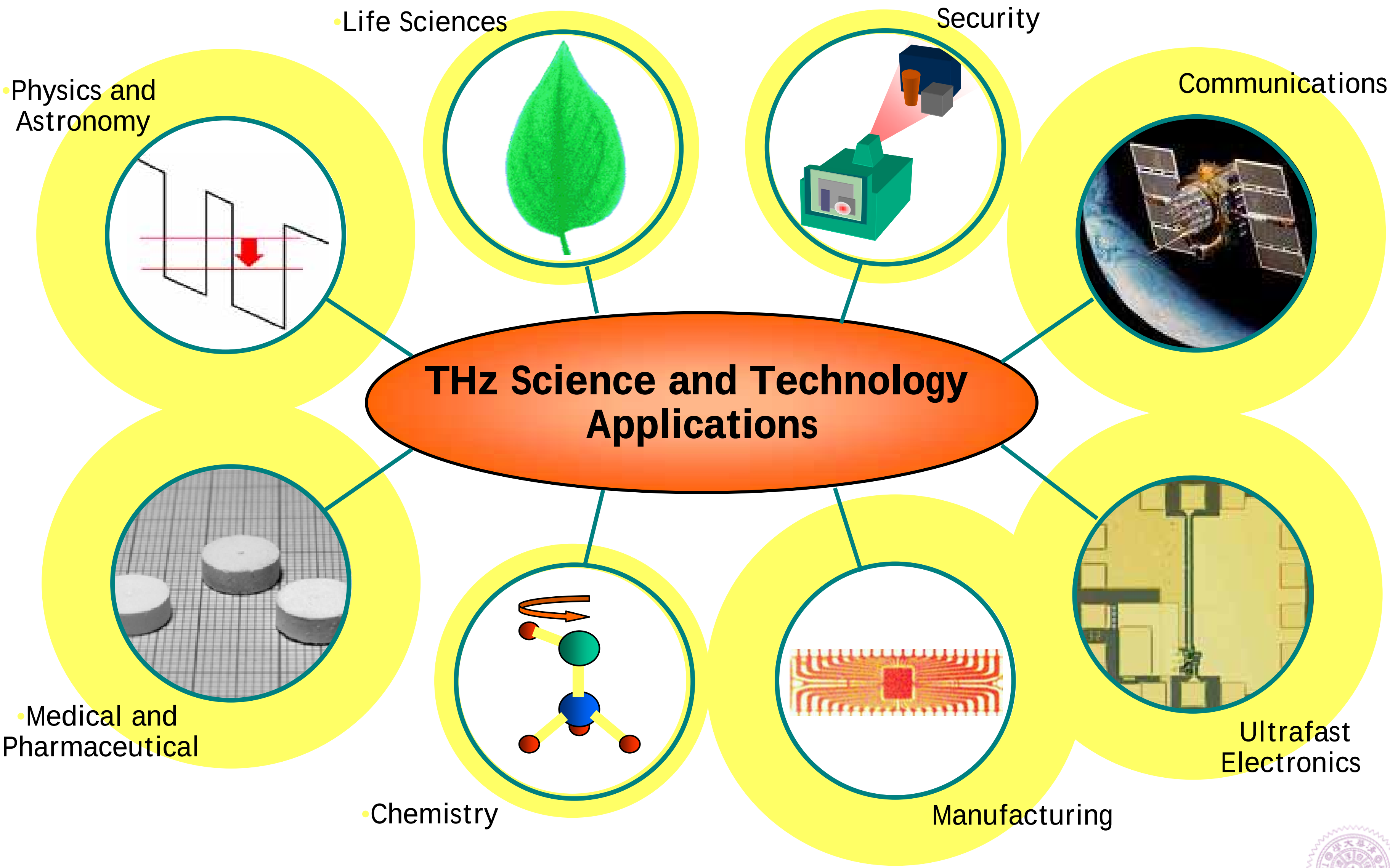
Terahertz wave (or T-ray), which is electromagnetic radiation in a frequency interval from 0.1 to 10 THz, lies a frequency range with rich science but limited technology.



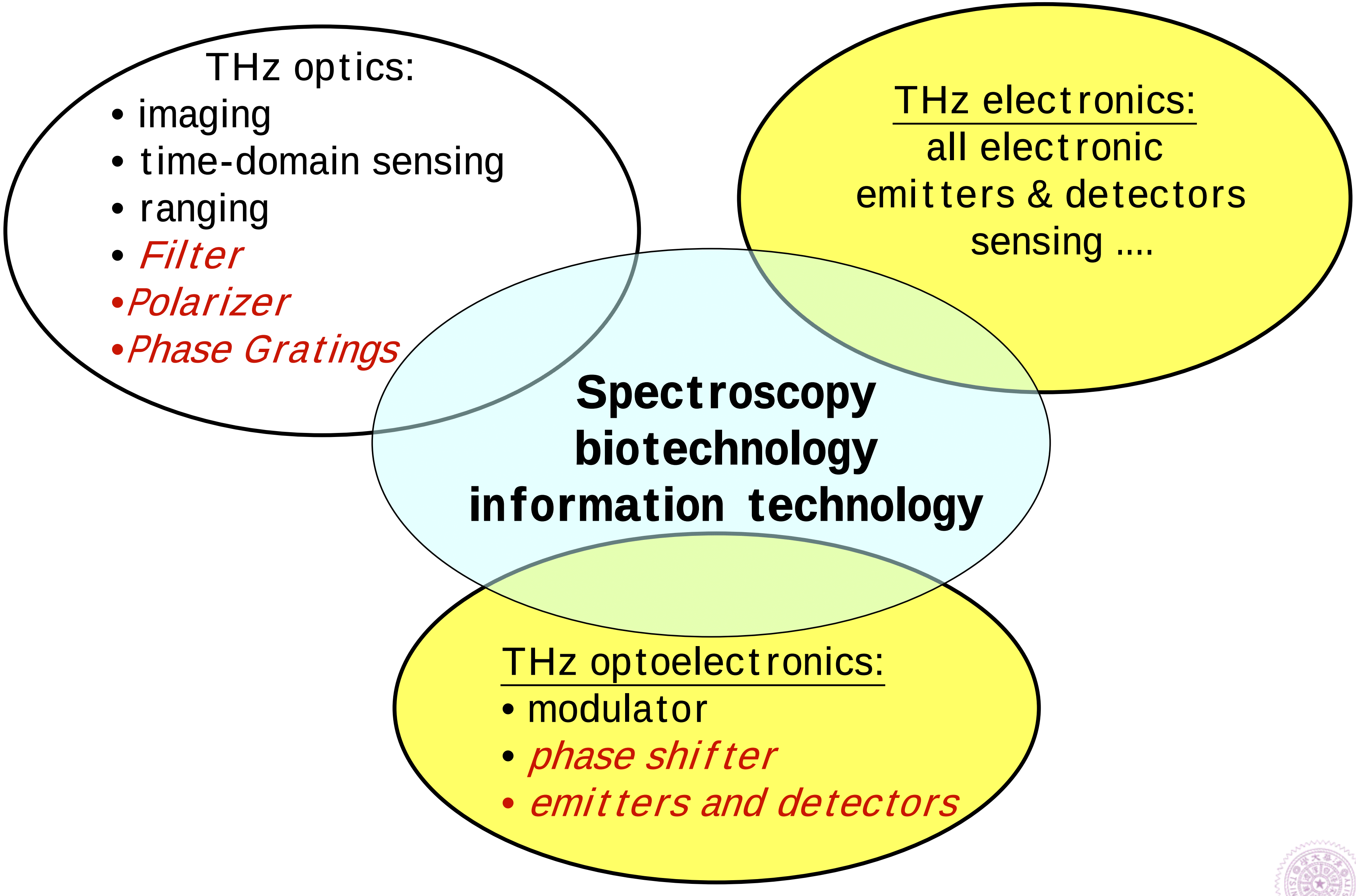
1 THz ~ 1 ps ~ 300 μm ~ 33 cm^{-1} ~ 4.1 meV ~ 47.6 °K

Courtesy: X.-C. Zhang (RPI)

Applications



THz Technologies



THz Wave Emitters

- Free electron laser, gas lasers
  Highest T-ray power (Nature, Nov. 14, 2002)
- Photoconductive dipole antenna:
  Great T-ray power with a moderate optical input
- Electro-optic crystal with femtosecond laser:
  Broad bandwidth, optical input with high peak power
- Electronic emitter (Gunn, Bloch oscillator, cold plasma)
  Compact, low cost
- Semiconductor THz laser! (Nature, May 9, 2002)

THz Wave Detectors

- Photoconductive dipole and array:

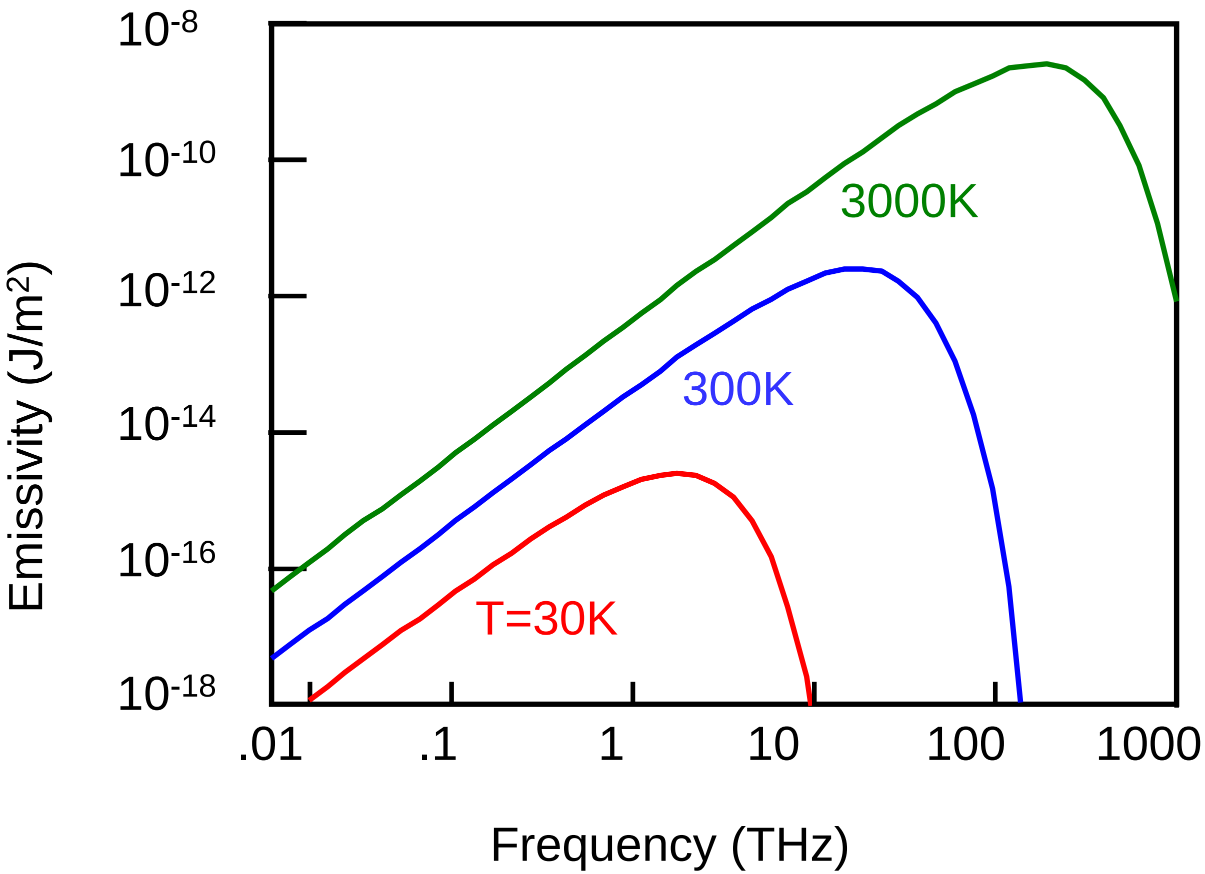
  Low dark current, low noise
- Electro-optic crystal with femtosecond laser:

  Large aperture, broad bandwidth
- Electronic detector

  Low cost, compact
- Bolometer and Pyroelectric detector

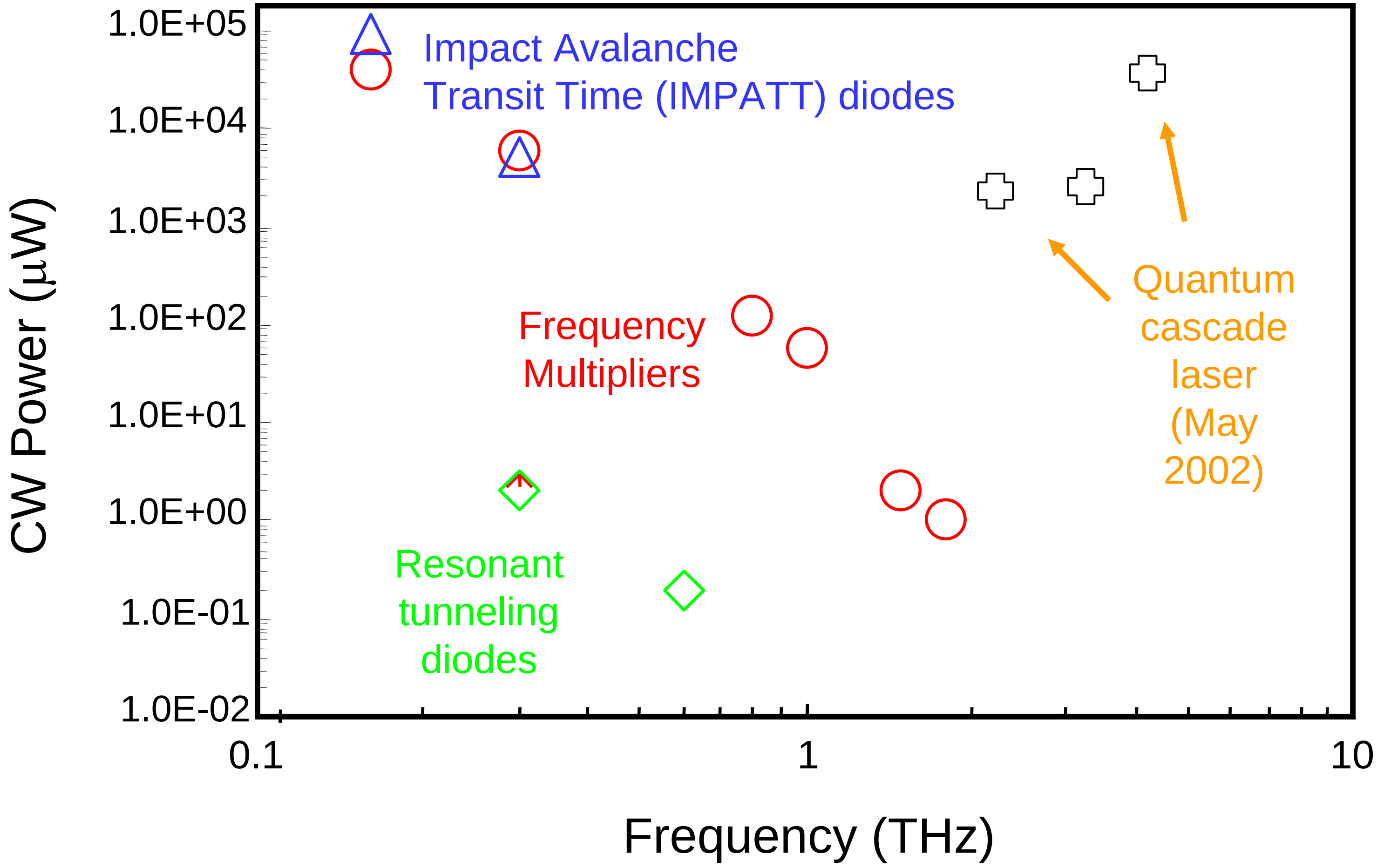
  Incoherent radiation, High Sensitivity

Blackbody Radiation:
Natural Source of THz Radiation



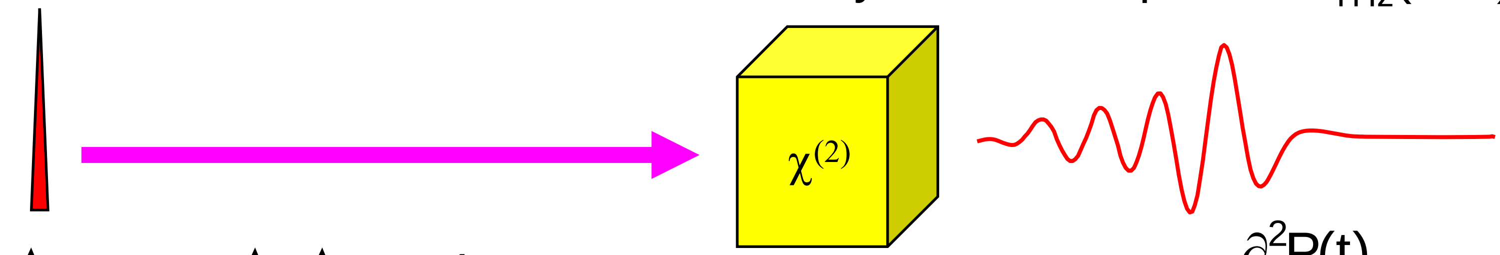
Natural sources of THz are very weak.

"Traditional" electronic approaches to "THz light"



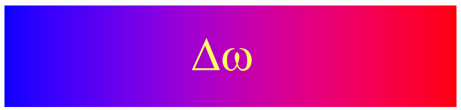
Generation of a THz Wave: Optical Rectification

Input laser pulse $I(t, \omega, \Delta\omega)$ EO crystal THz pulse: $E_{THz}(t, \Omega)$



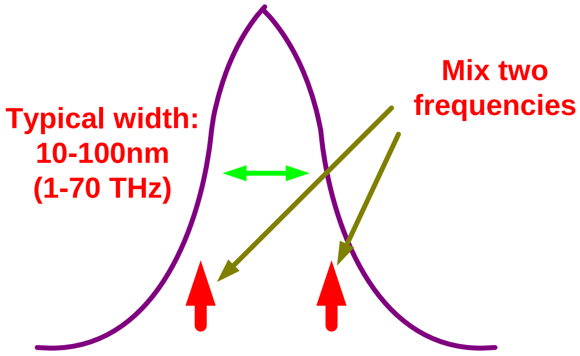
$\Delta\tau$ $\Delta\tau\Delta\omega = 1$ $P(t)$

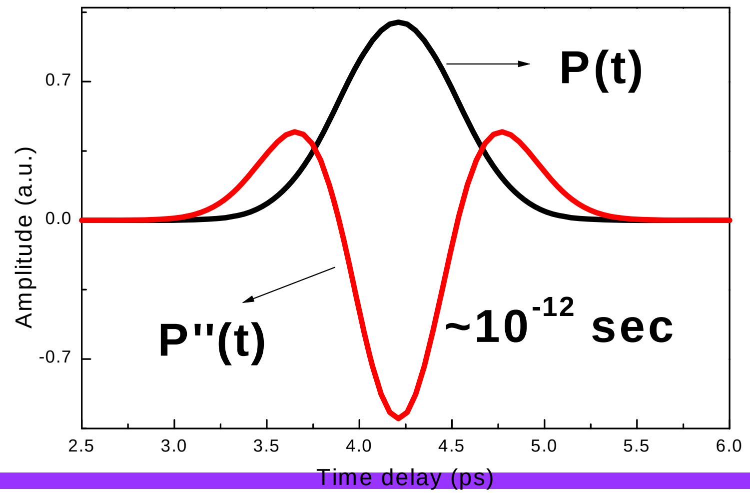
$$E_{THz}(t) \propto \frac{\partial^2 P(t)}{\partial^2 t}$$



Beating frequency $\Omega < \Delta\omega$ (laser bandwidth)

polarization: $P(\Omega) = \chi^{(2)}(\Omega, \omega+\Omega, -\omega)\, E(\omega+\Omega)E^*(\omega)$

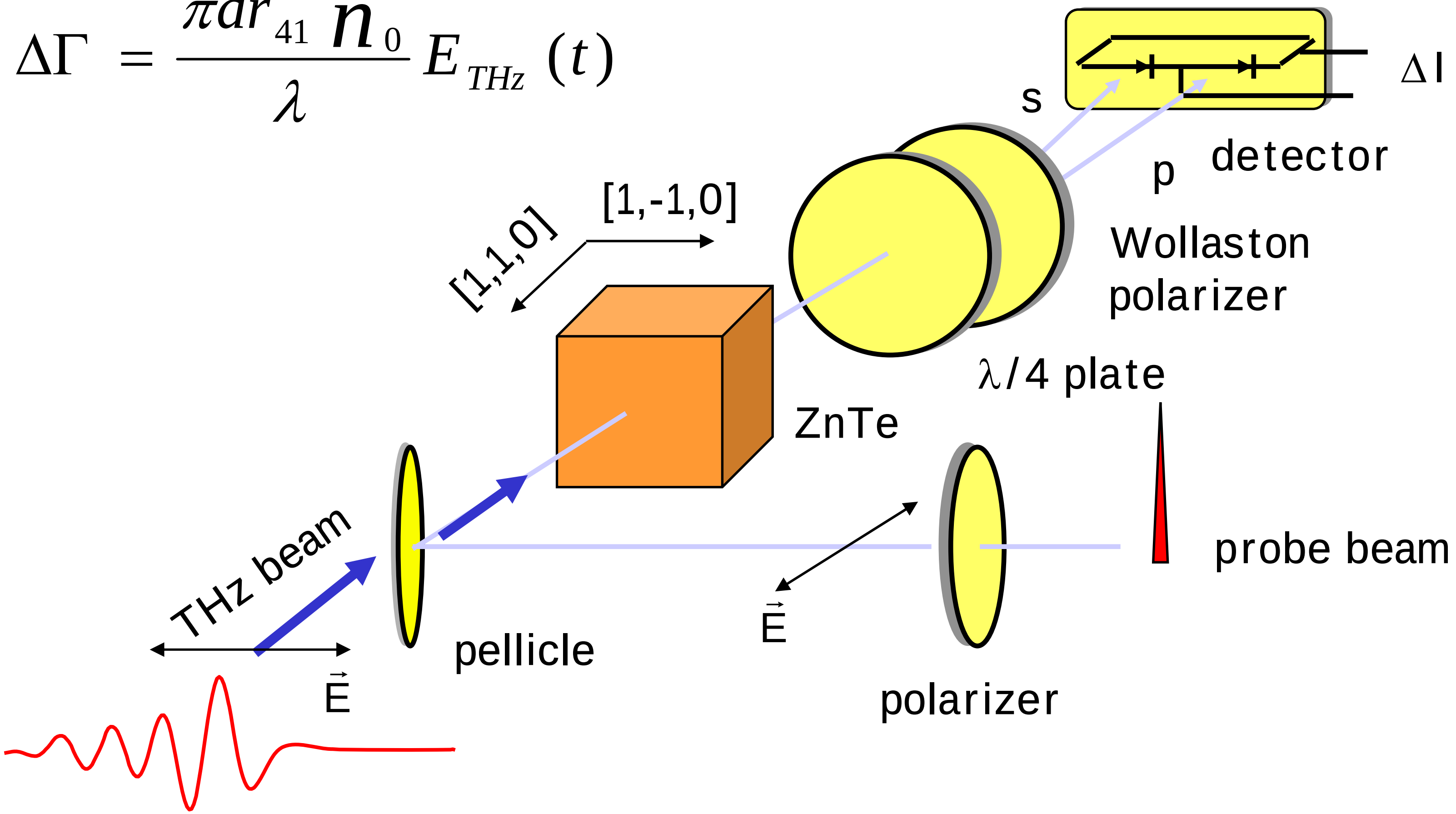




Detection of THz Wave: Electro-Optic Sampling

$$\Delta I(t)=I_0 \sin(\Delta\Gamma)$$

$$\Delta\Gamma = \frac{\pi d r_{41} n_0^3}{\lambda} E_{THz}(t)$$



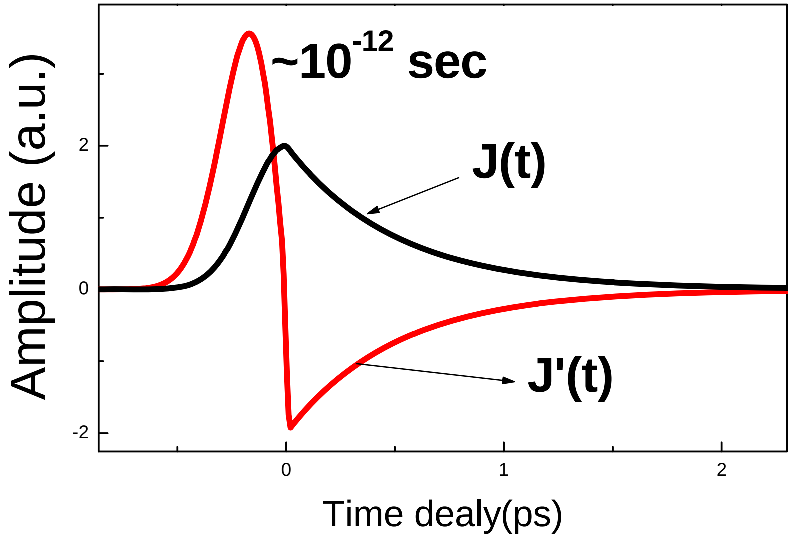
Polarization of the THz field, the probe, and ZnTe [1,-1,0] are parallel
Phase matching condition (Δk=0): optical group velocity = THz phase velocity

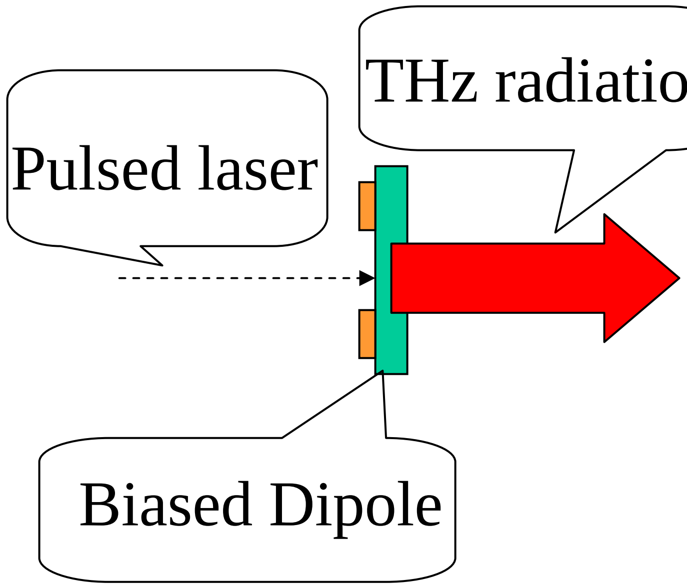
Generation of THz Wave: current surge effect

- **Photo-excited Hertzian dipole antenna in free space.**

$$J(t) = n(t)e\mu E_b$$

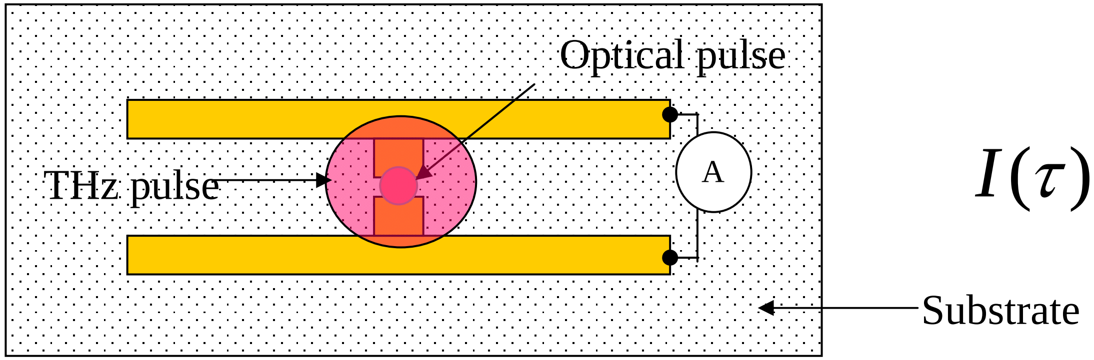
$$E(r,t) \propto \frac{1}{r}\frac{\partial J(t)}{\partial t}$$





Ultrashort-pulse-induced THz light is typically a single-cycle pulse!

Detection of THz Wave: Photoconductive Antenna



$$I(\tau) \propto e\mu\tau_c \int_{t_1}^{t_2} E(t)n(t-\tau)dt$$

$I(\tau)$: detected signal current, e: electron charge, μ: carrier mobility, τ_c: carrier life time, m: repetition rate, τ: relative time delay between THz pulse and gating laser pulse, n(t): photo-induced transient carrier density, E(t): THz field.

Substrate with

- Shorter carrier life time: n(t) ~ delta function =>$E(t)\propto I(t)$
- Long carrier life time: n(t) ~ step function =>$E(t)\propto dI(t)/dt$

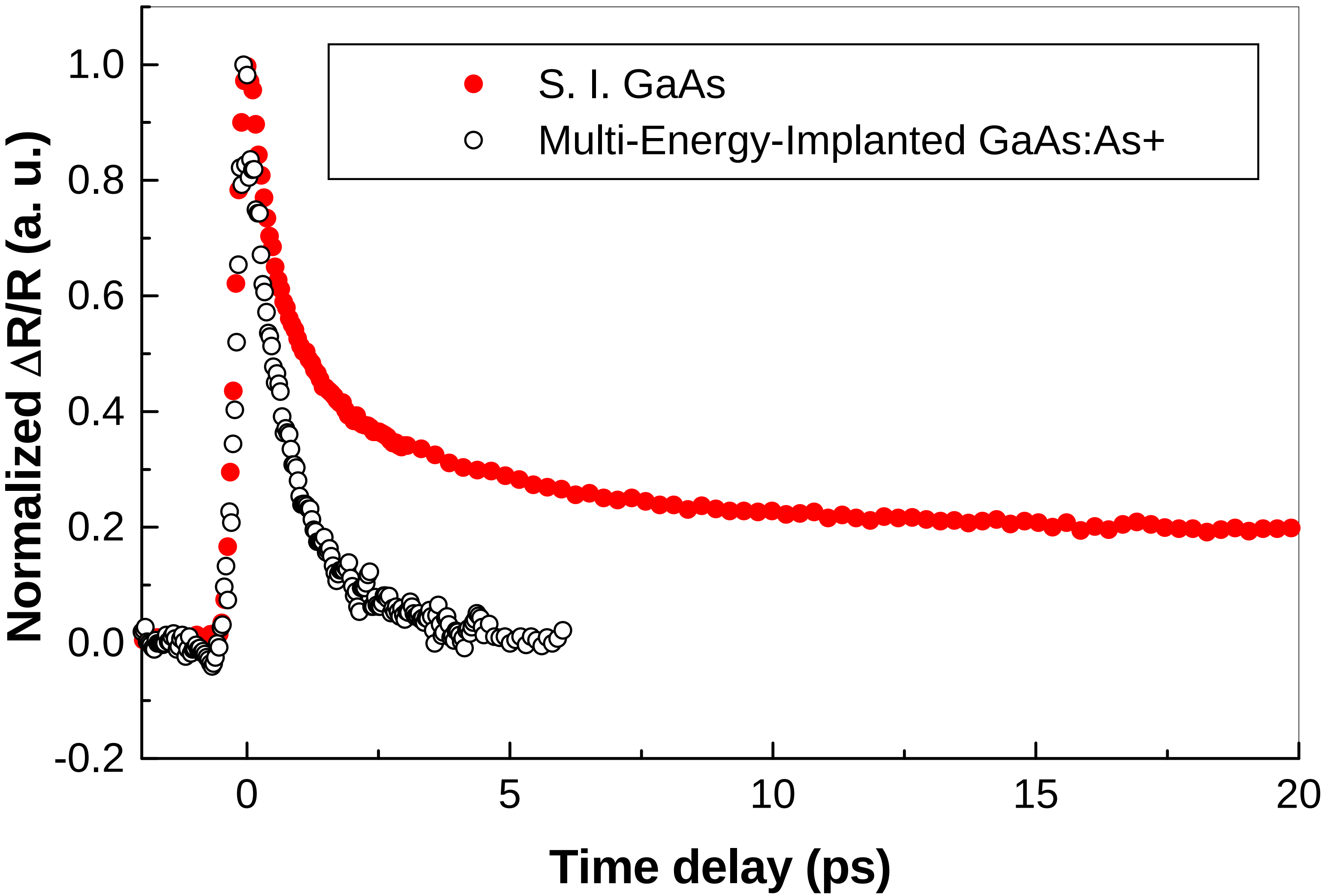
Terahertz-Pulse Emission from Photoconductive Antennas

- For the construction of the PC antenna, one needs a PC substrate :
  1. short carrier lifetime,
  2. high mobility
  3. high breakdown voltage

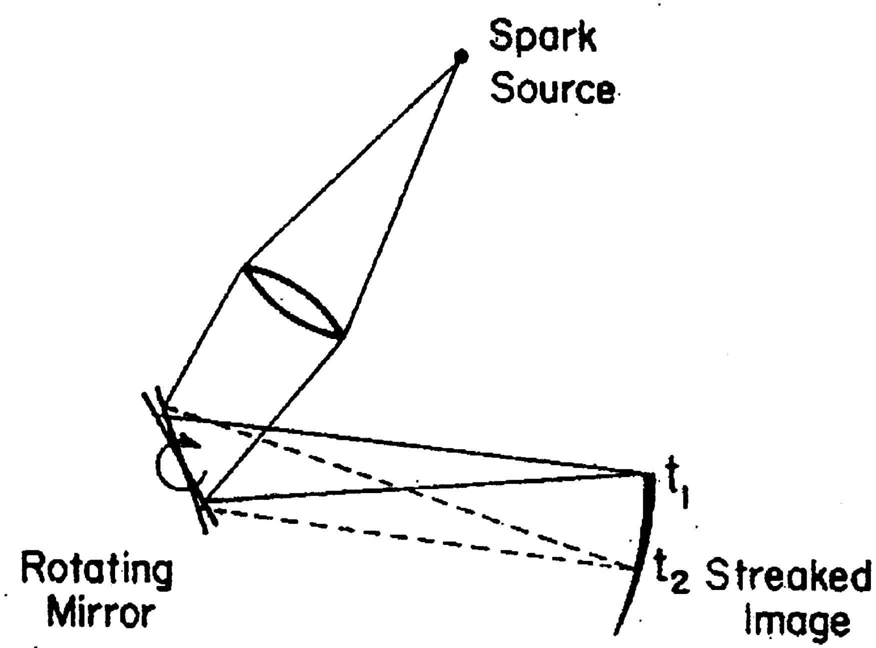
Table 1. Characteristics of ultrafast photoconductive materials

Photoconductive materials	Carrier lifetime (ps)	Mobility ($cm^2/(V \cdot s)$)	Resistivity ($\Omega \cdot cm$) (Breakdown field, V/cm)	Band gap (eV at R.T.)
Cr:doped SI-GaAs	50–100.0	≈ 1 000	10^7	1.43
LT-GaAs	0.3	150– 200	10^6 (5×10^5)	1.43
SI-InP	50–100.0	≈1 000	4×10^7	1.34
Ion-Implanted InP	2– 4.0	200	$> 10^6$	1.34
RD-SOS	0.6	30		1.10
Amorphous Si	0.8– 20.0	1	10^7	1.10
MOCVD CdTe	0.5	180		1.49
LT-$In_{0.52}Al_{0.48}As$	0.4	5		1.45
Ion-implanted Ge	0.6	100		0.66

SI-GaAs vs GaAs:As THz Emitters: Carrier Lifetimes



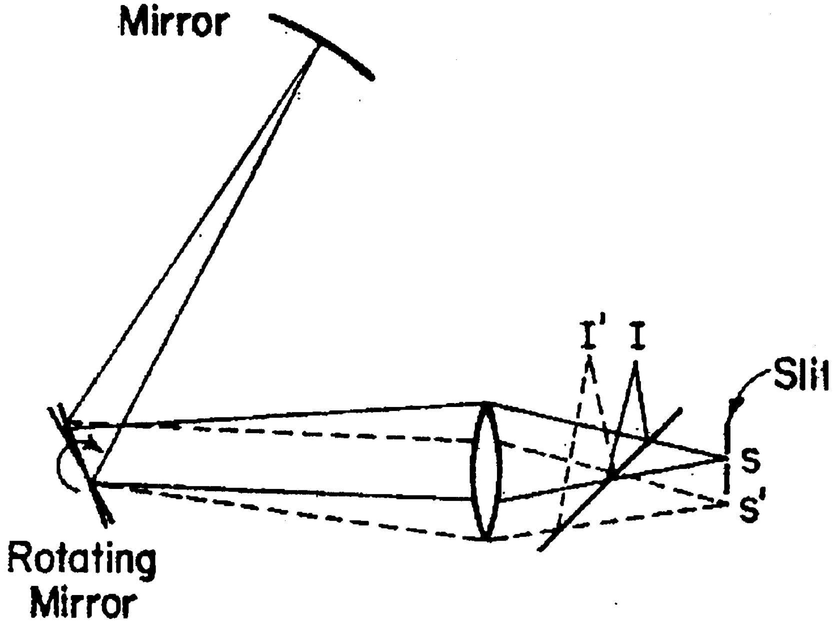
Mechanical Streak Camera



(a)

Electrical Spark

(Wheatstone, 1934)

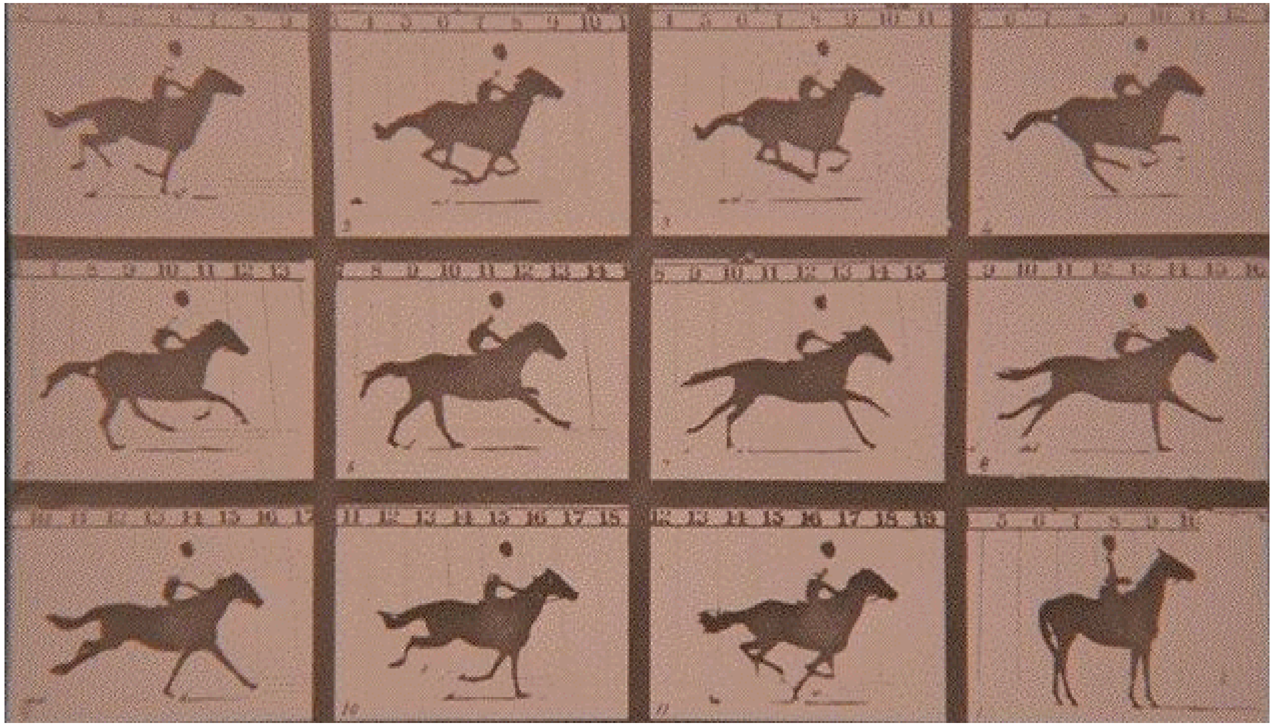


(b)

Speed of Light

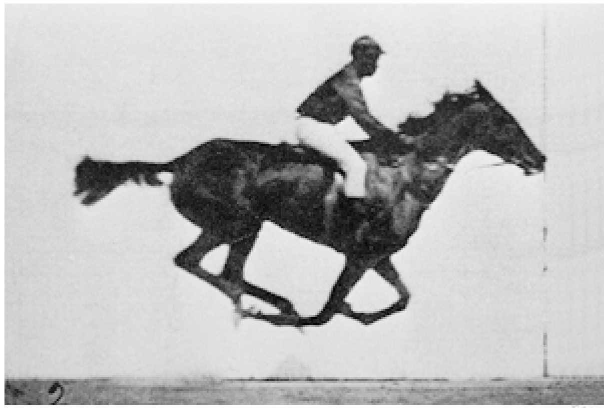
(Foucault, 1850-1860)

Strobe Photography (I)

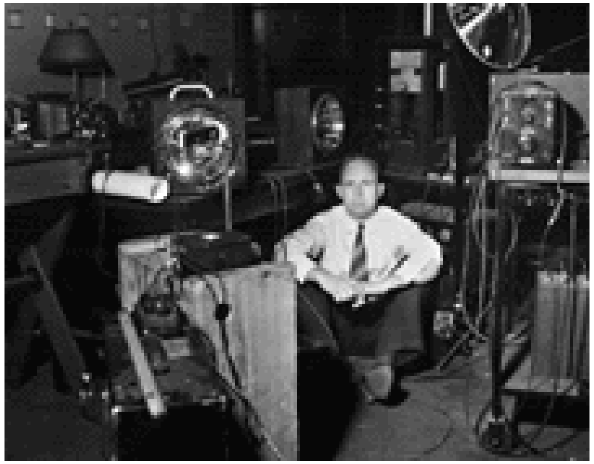


Time Resolution:
1/60th of a second

The "Trotting Horse" Controversy
Palo Alto, CA , USA 1872

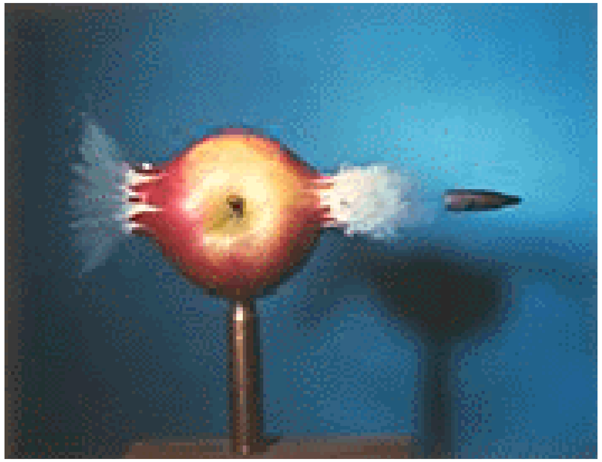


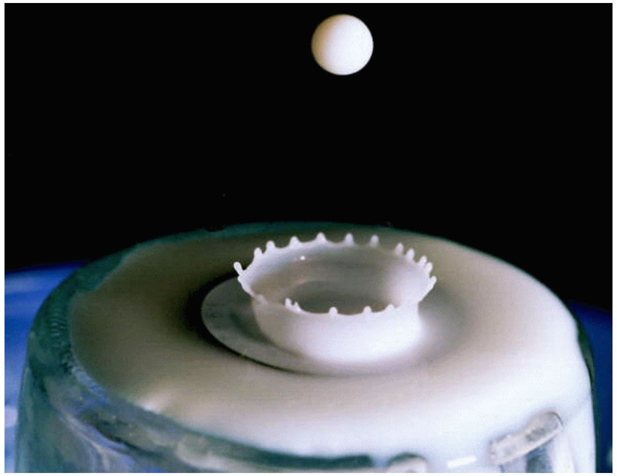
Strobe Photography (II)



Harold
Edgerton
MIT, 1942

"How to Make
Apple sauce
at MIT"
1964

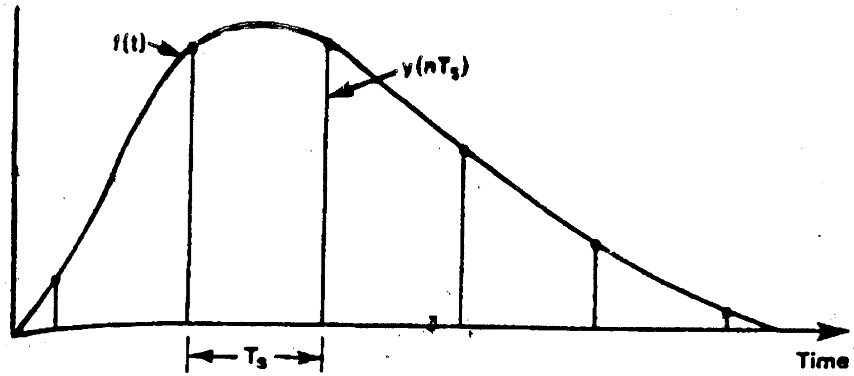




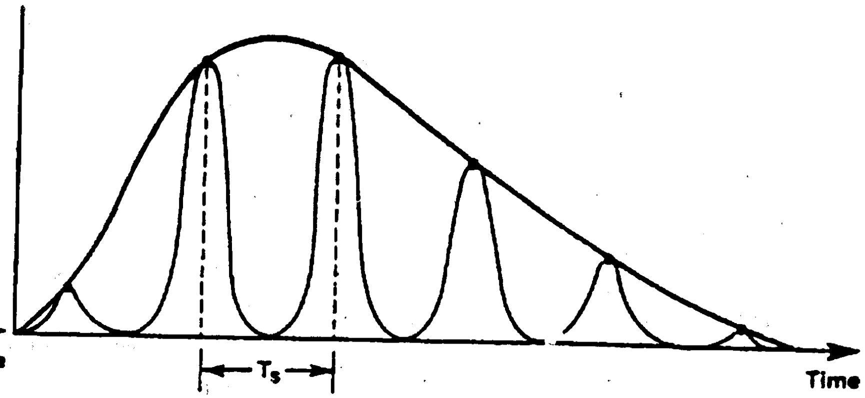
"Splash on a
Glass"

Time Resolution: a few microseconds

Strobe (Sampling) Principle



Ideal Sampling



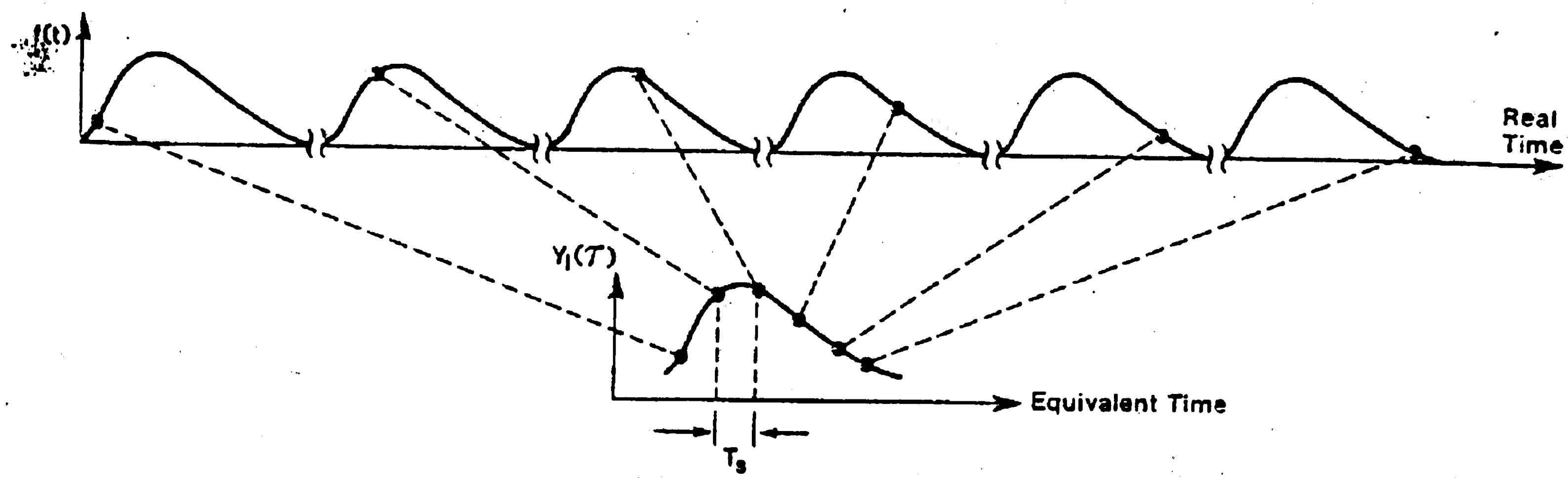
Practical real-time sampling

To sample properly, we require：

f_s(Sampling rate) $\geqq 2f_h$ (Highest Frequency Component of Signal)

or $T_s(=1/f_s) \leqq \dfrac{1}{2f_h}$

Equivalent Time Sampling



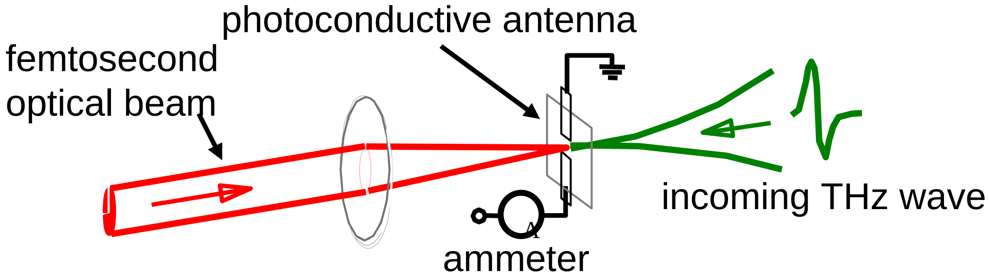
Where

T_e : Time interval between sampling pulses

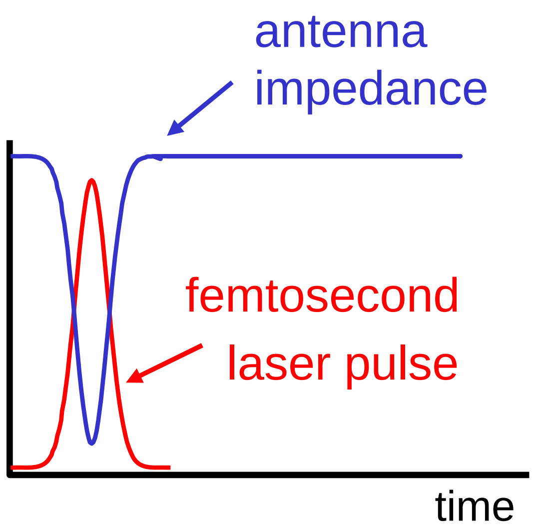
T : Time for the signal to repeat

T_e(Equivalent time) $= mT + T_s$

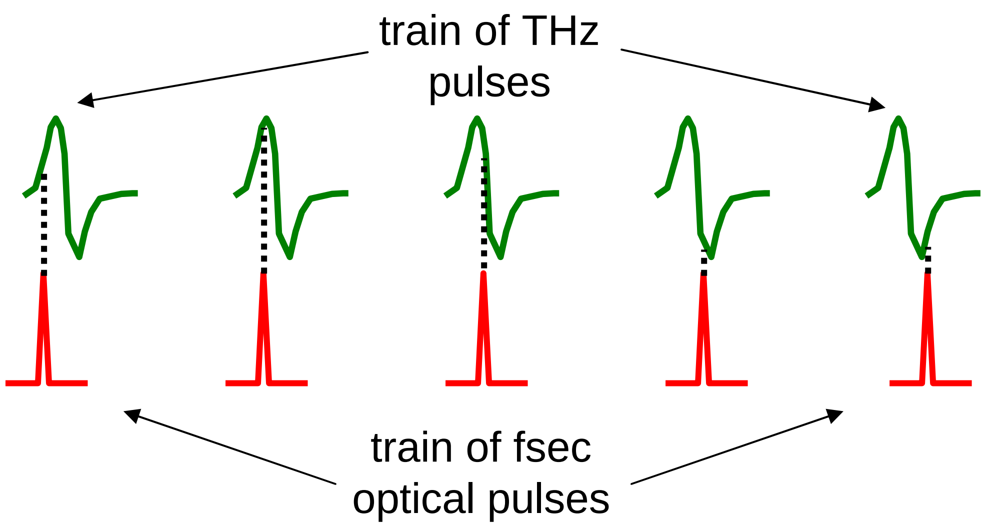
Measuring THz pulses using photoconductive sampling



Antenna impedance vs. time

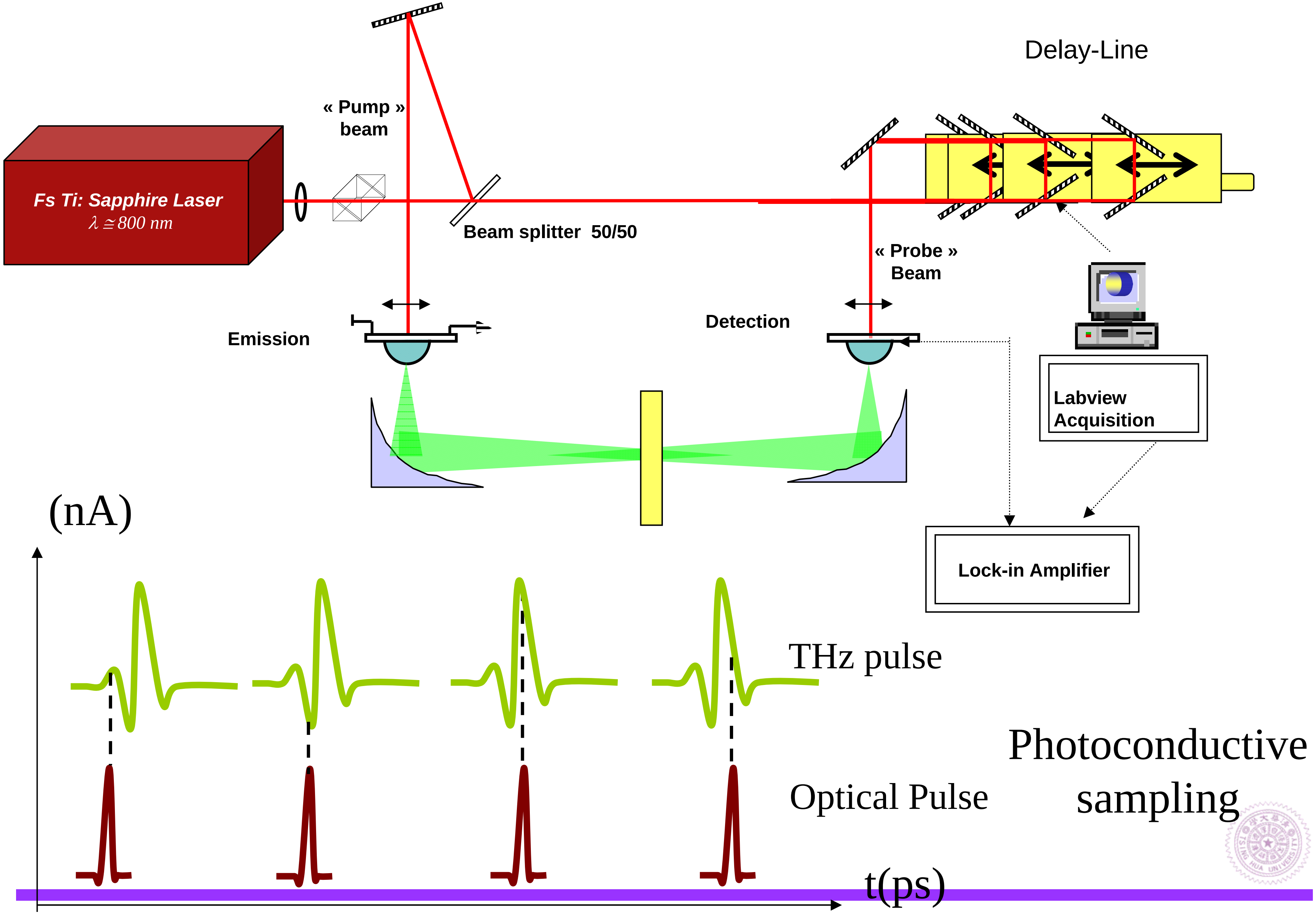


Scanning the delay is performed as in cross-correlation.



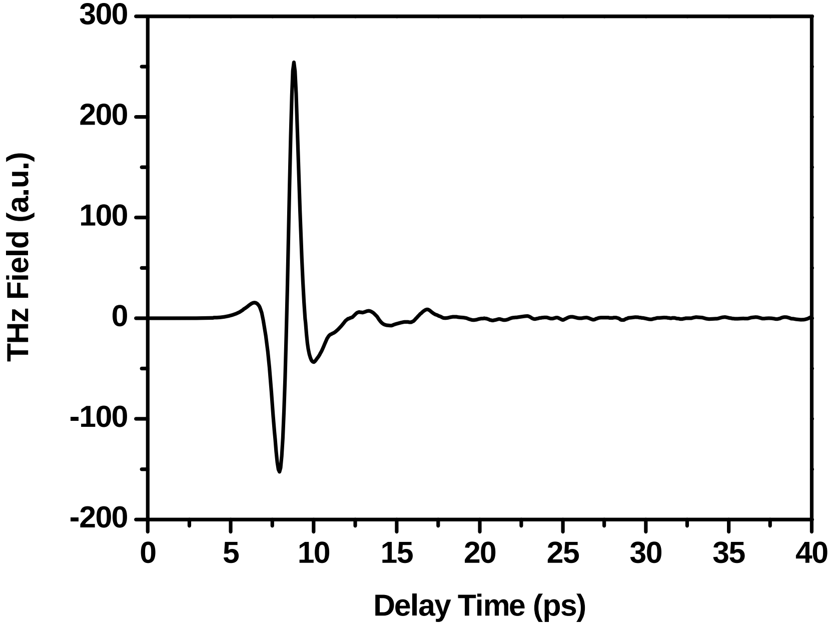
Because the fs optical pulse is shorter than the THz pulse, this works.

PC-antenna-based THz-TDS set-up



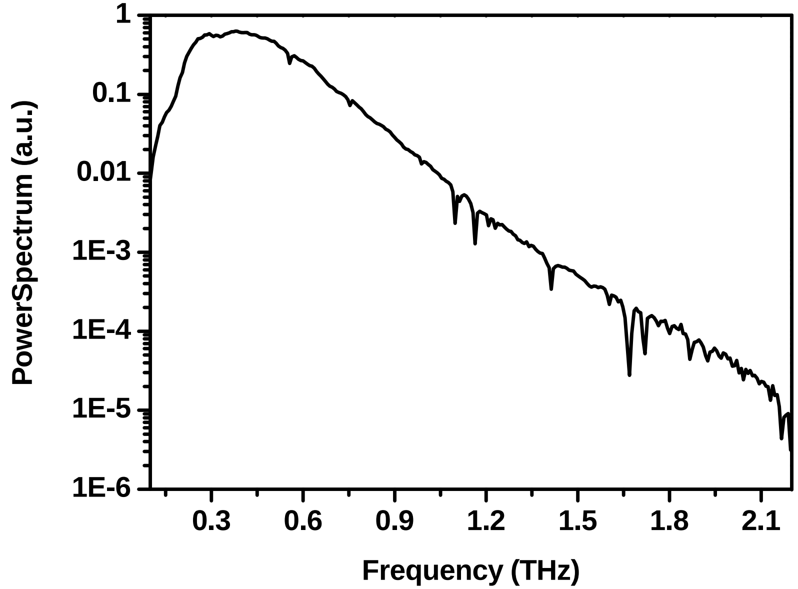
Photoconductive sampling

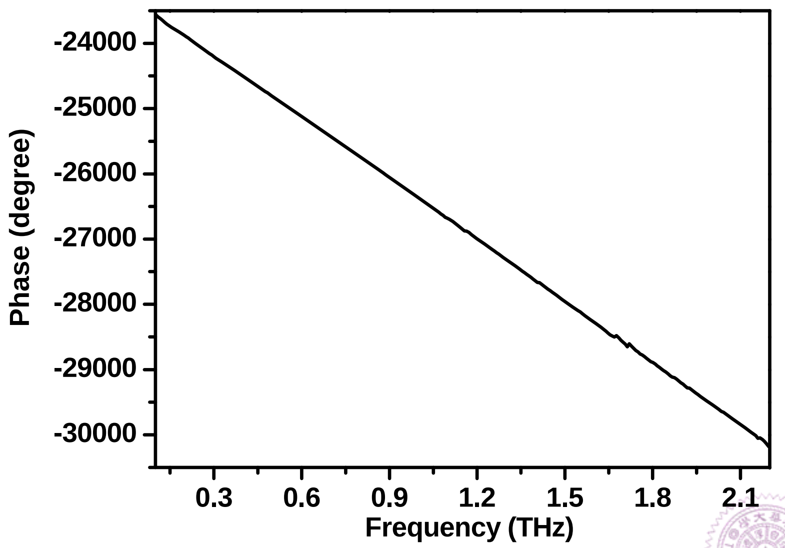
Typical THz Waveform and Spectrum



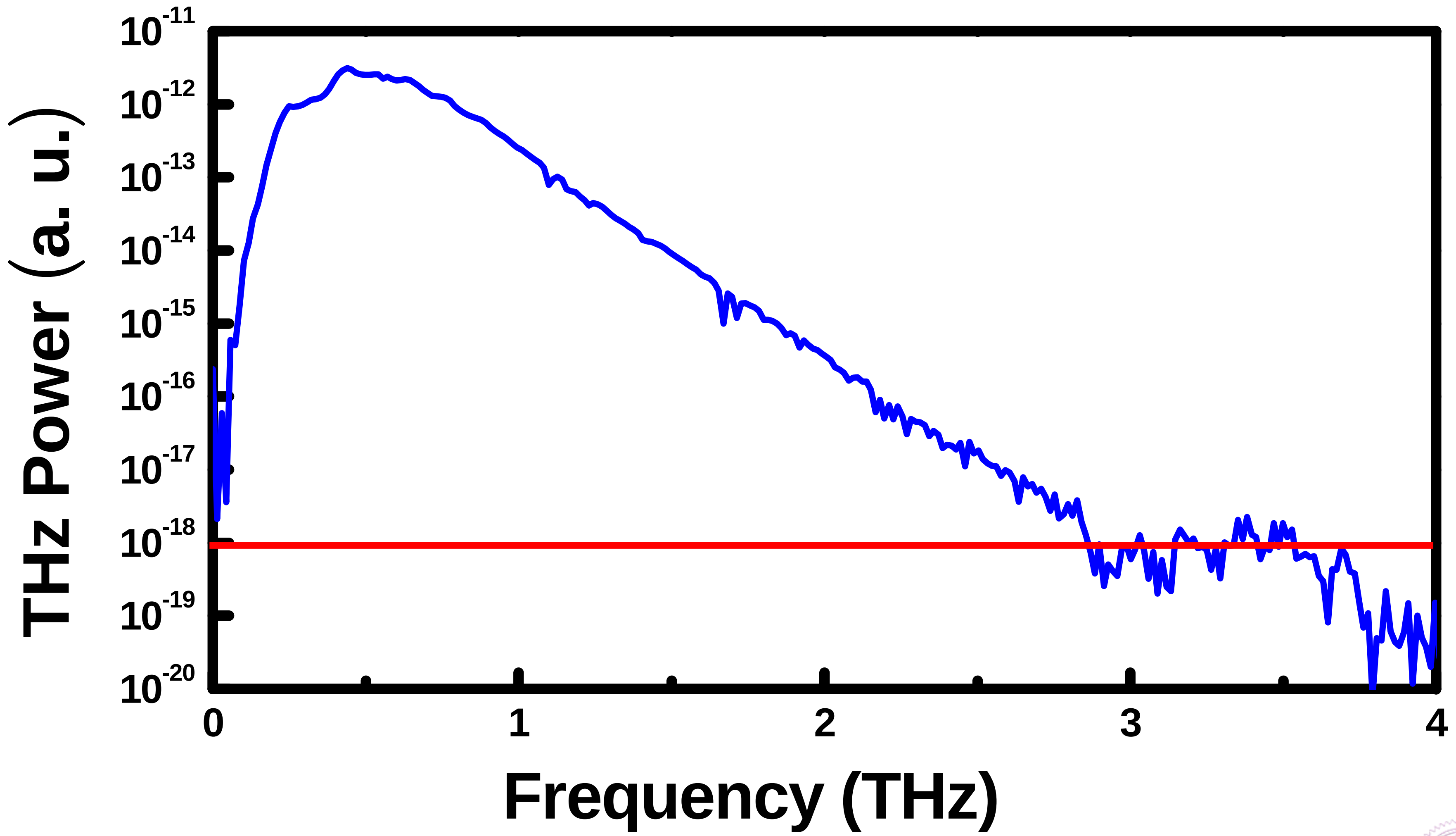
Time-domain signal

FFT

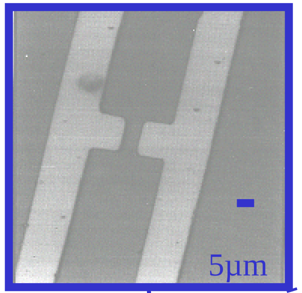


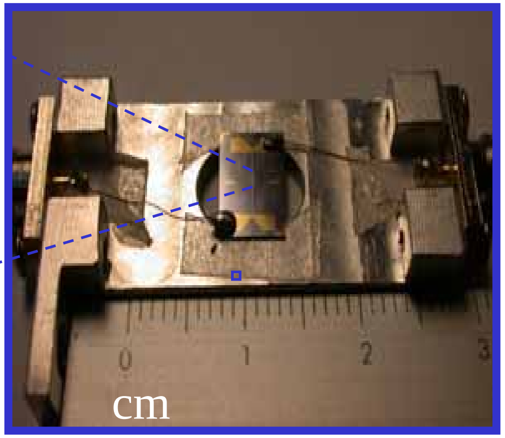


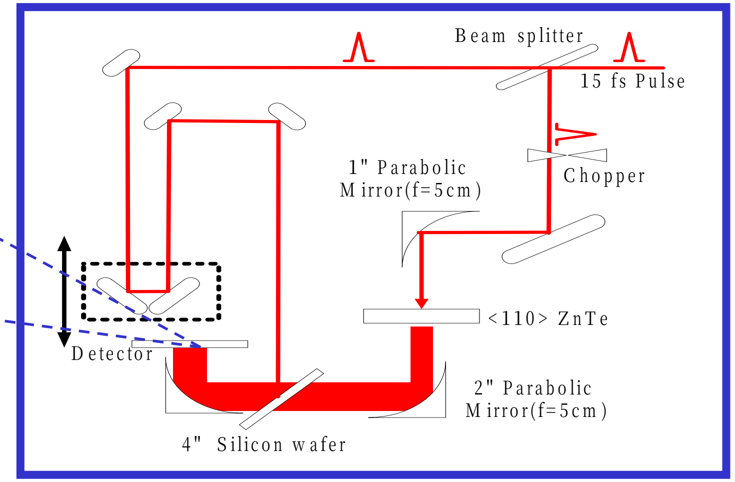
THz time-domain spectroscopy (THz-TDS)

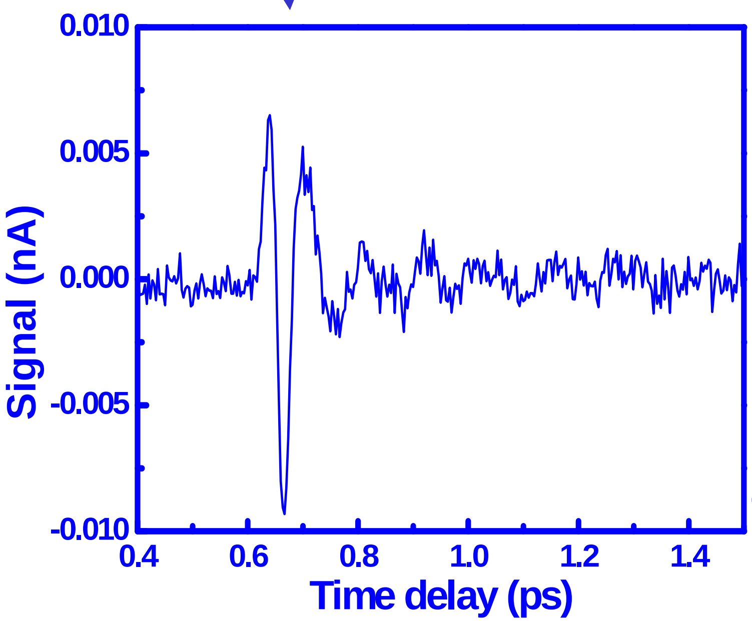


Wideband GaAs:As$^+$ and InP:H$^+$ THz Antenna







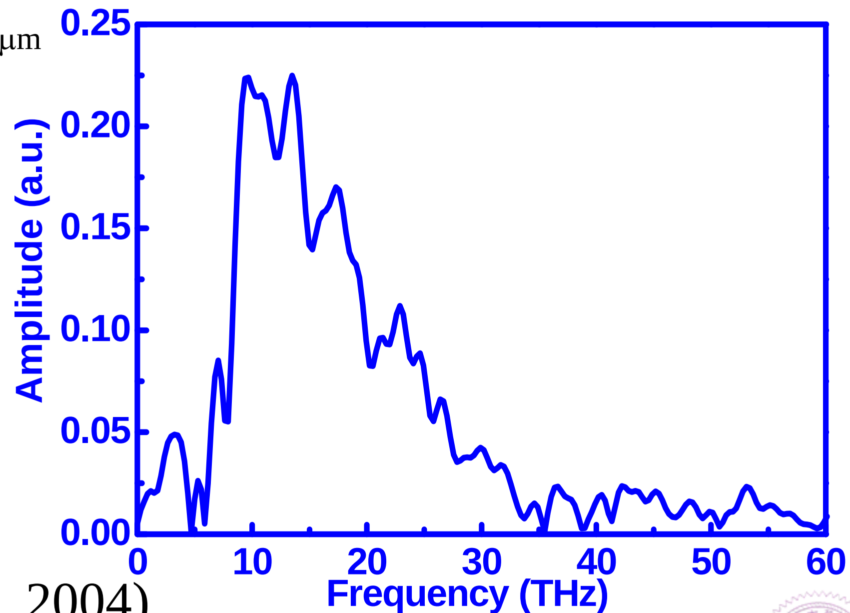


L = 20 or 30 μm

W = 10 μm

G or D = 5 μm

F.F.T.

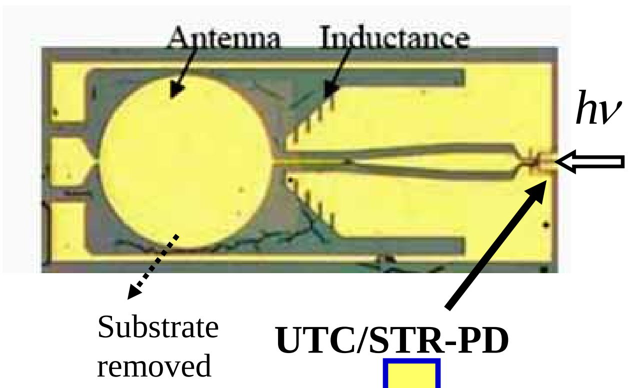


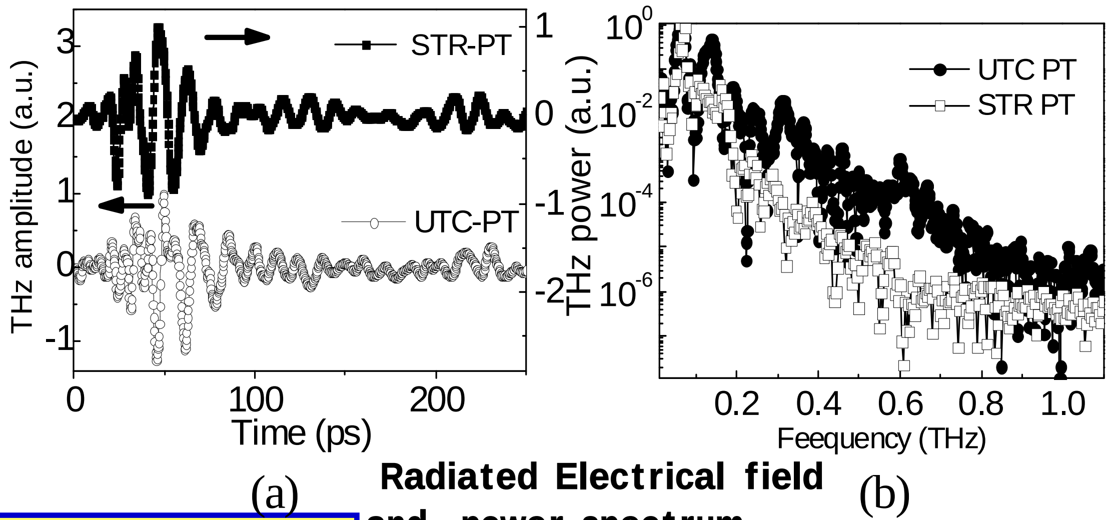
APL(Aug 18, 2003), Opt. Exp (June 28, 2004),

both selected by Virtual J of Ultrafast Sci.,

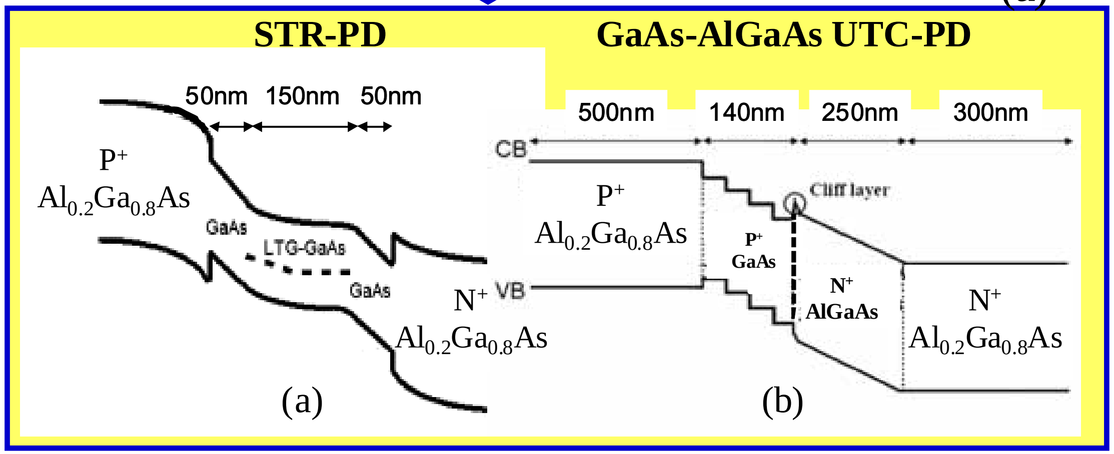
High-Power Sub-THz Photonic-Transmitters

Top-view of demonstrated PTs





Radiated Electrical field and power spectrum

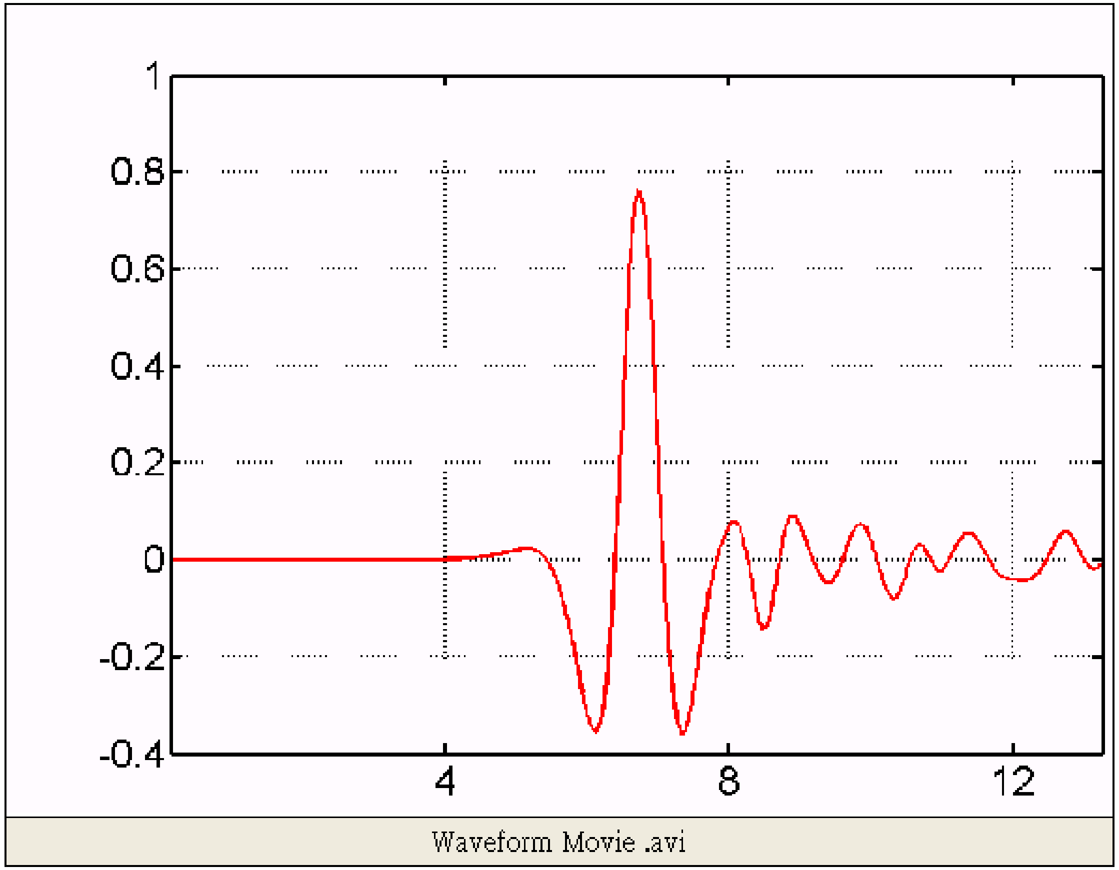


- *IEEE PTL* ***20****(2008)1342.*
- *IEEE JQE 46(2010)19.*

- **High-power photonic transmitters based on two different kinds of high-power PD integrated with the same antenna were analyzed.**
- **Both devices generated high peak-power (~2mW) and sub-THz 3-dB bandwidth.**

In collaboration w/ J. W. Shi (NCU)

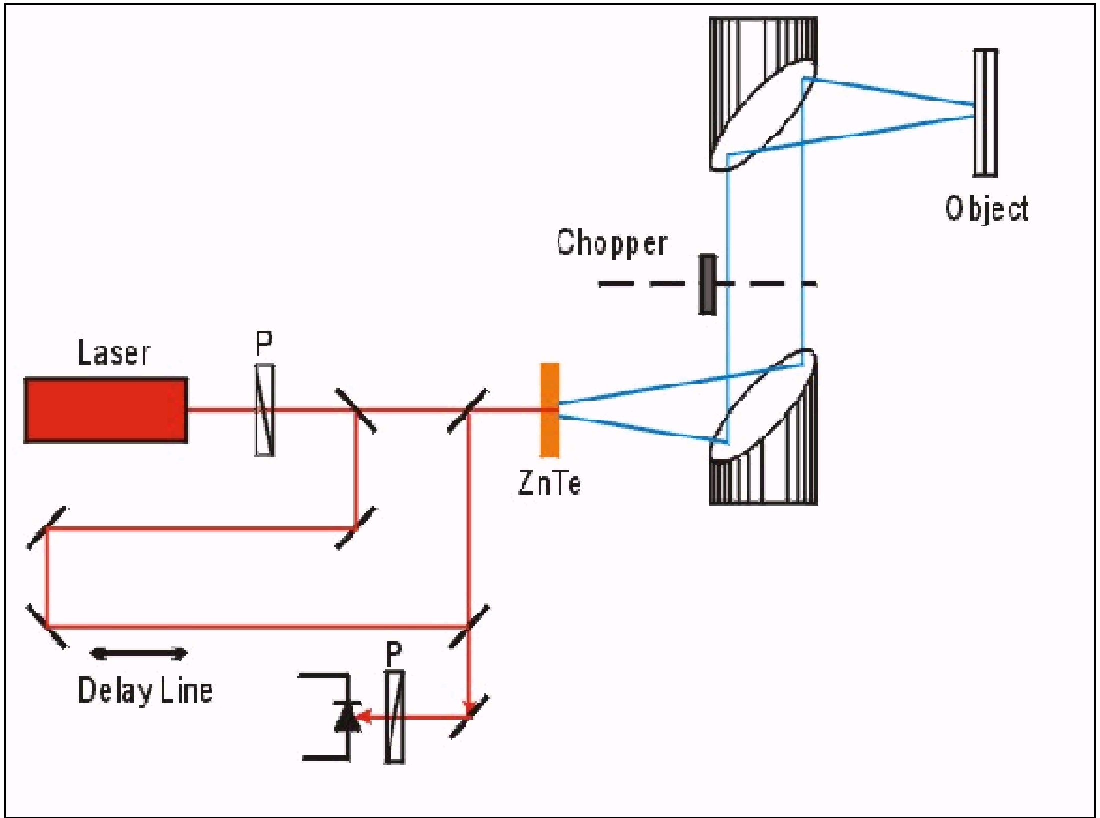
Taking a THz Waveform



Field (a.u)

Time (ps)

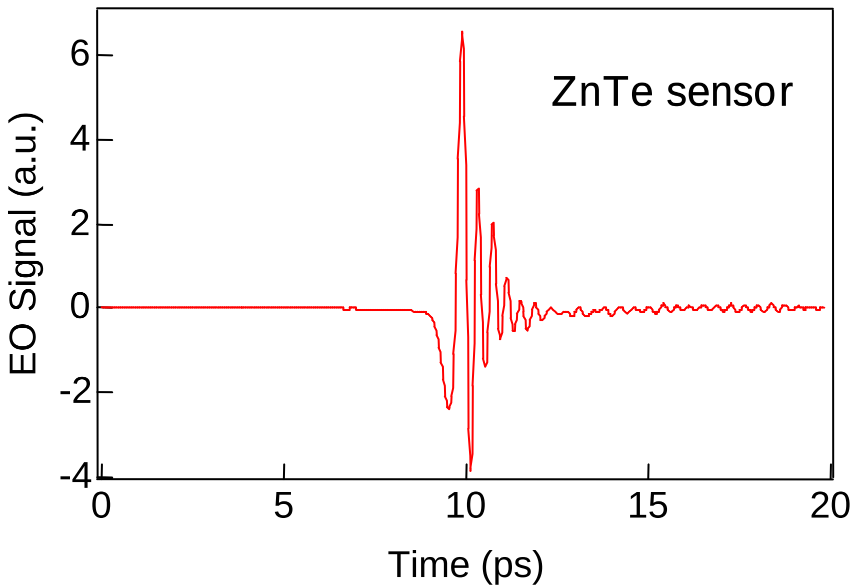
Free-Space THz Sensing and Imaging (Reflection Mode)



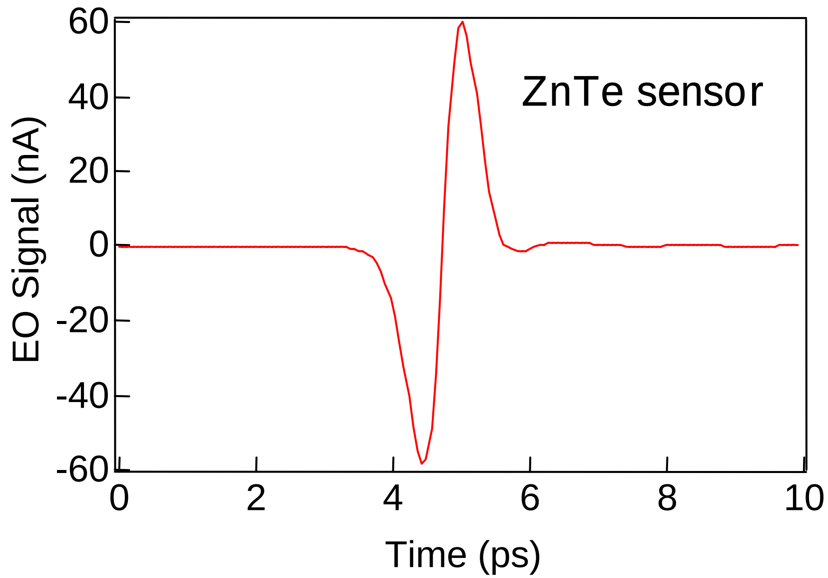
transceiver.avi

Sub-ps vs ps THz Waveforms

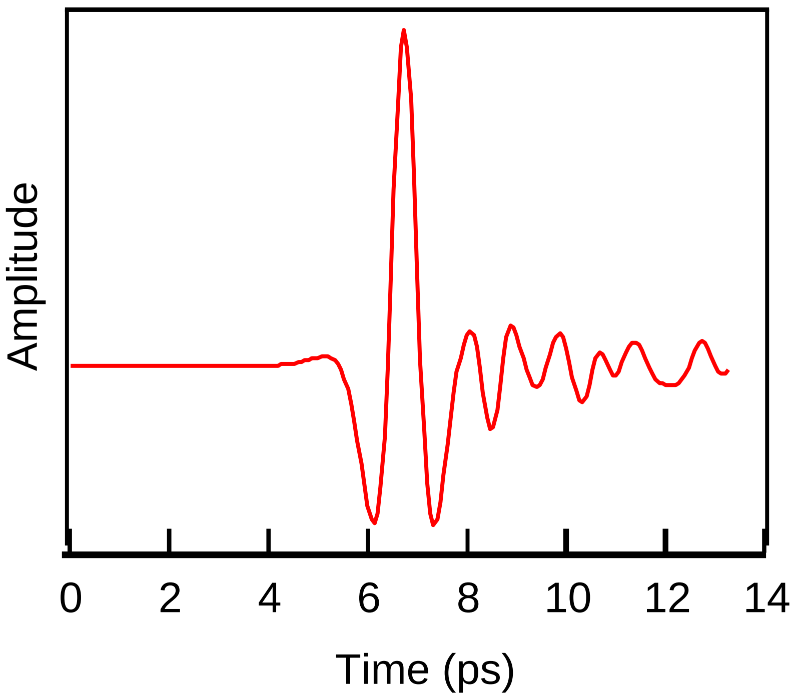
0.1 ps THz pulse

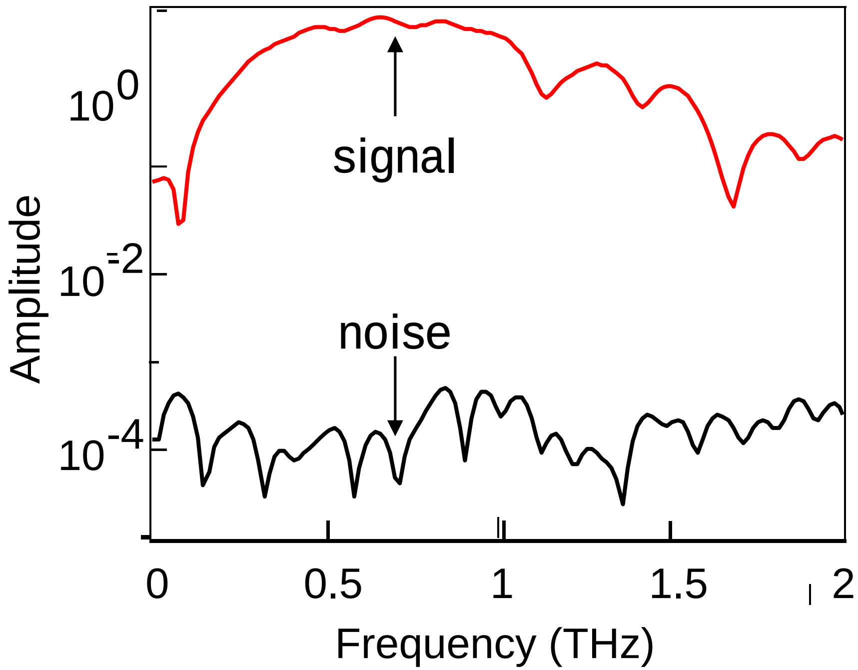


1 ps THz pulse



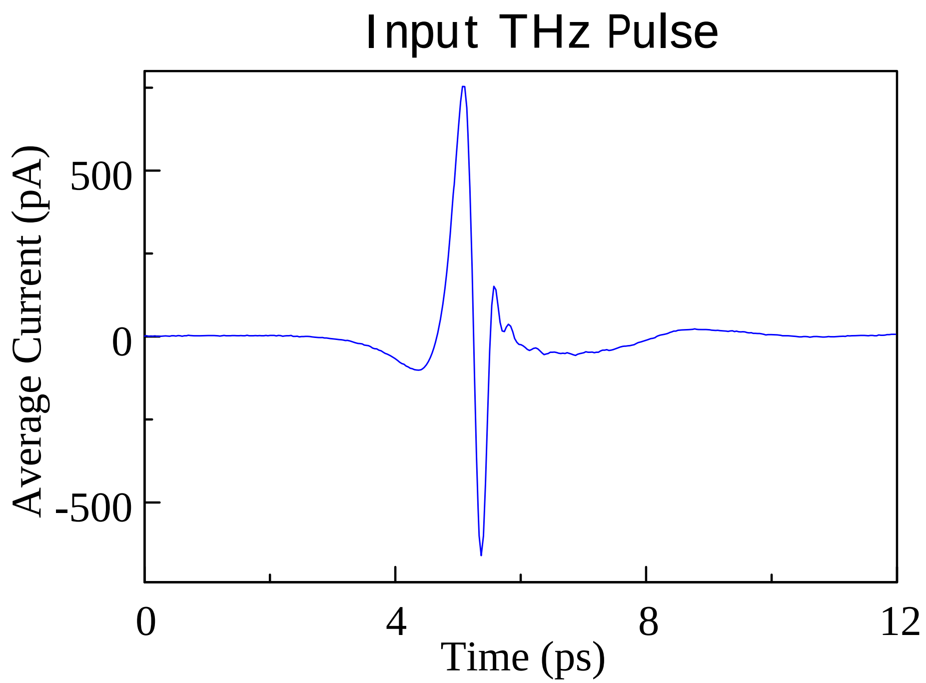
Dynamic Range > 100,000

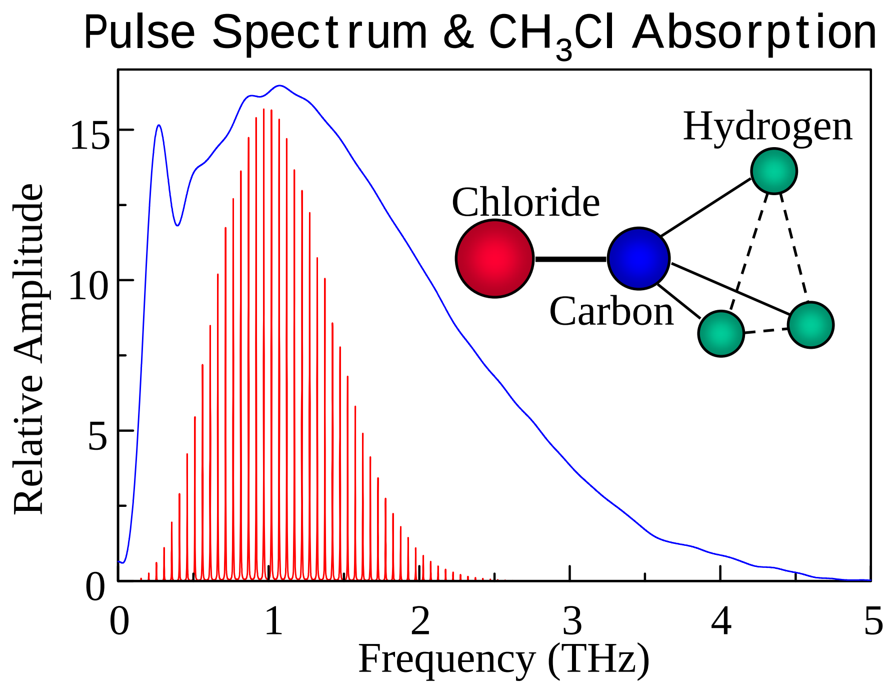




- Dynamic range is different than S/N
- The shorter pulse-duration, the broader wave spectrum

THz Time-domain Spectroscopy: Broad-band features





Direct measurement of the electric field for both amplitude and phase with sub-ps time resolution, high sensitivity, and high dynamic range.

The bandwidth of the THz pulse covers the full absorption spectrum of the molecules.

THz-TDS of a linear molecule OCS

Carbon sulfide : a molecule very well-known in spectroscopy

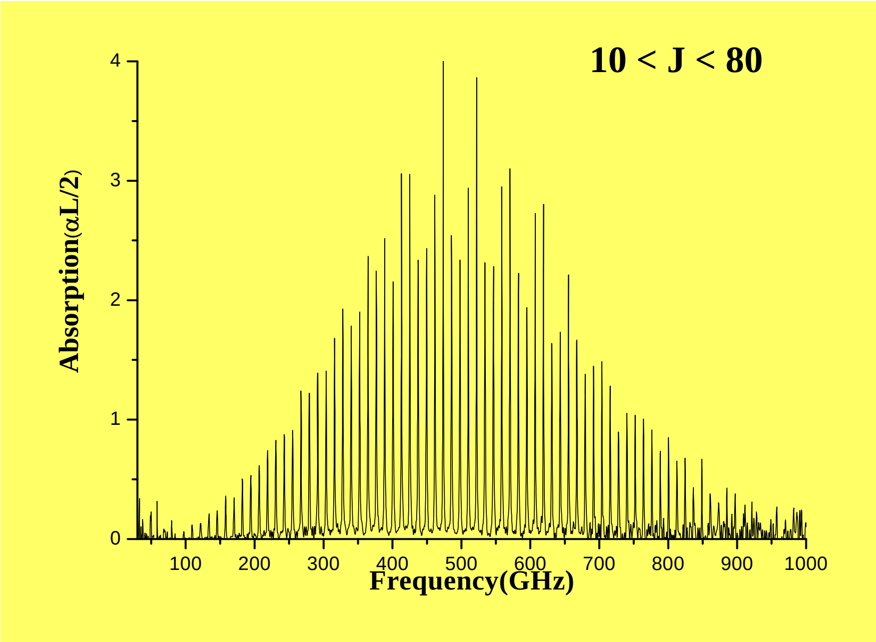
Atmospheric interest
(Significant VOC in the troposphere)

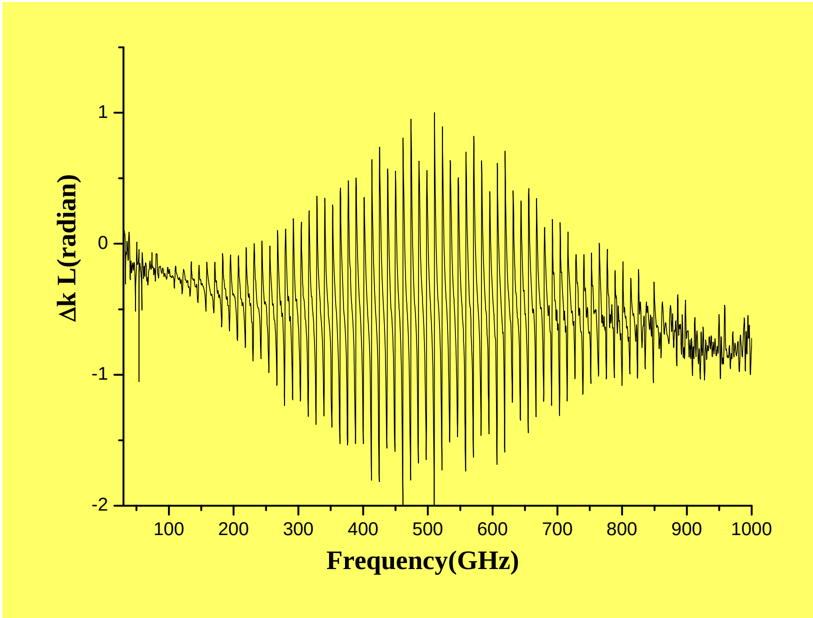
Theoretical interest
(Linear molecule with few atoms)

Astrophysic interest
(presence in the interstellar medium)

Experimental absorption and dispersion profile at a pressure of 200 mbar

$$\nu_J = \omega_J / 2\pi = 2B(J+1) - 4D(J+1)^3 \qquad B = 6.0815\,GHz \quad D = 1.3\,kHz$$

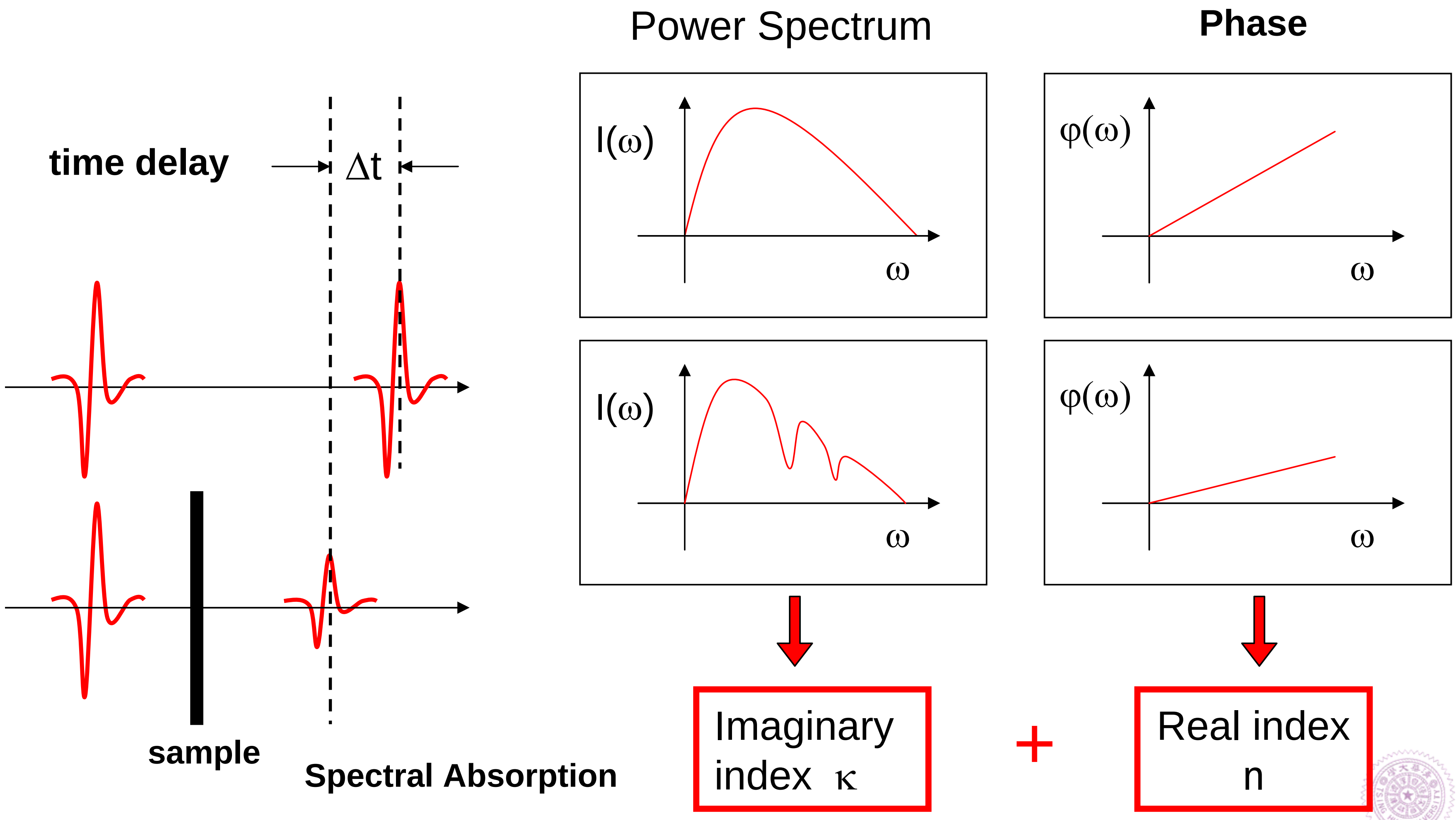




☺ **More than 60 pure rotational transitions are excited simultaneously by the THz field**

☹**The weak resolution of the THz-TDS (**~2.2GHz) do not allowed a correct measurement of the molecular parameters

THz-TDS: Extraction of
Far IR Optical Constants of Materials



How to derive n and k from THz-TDS (I)

time-domain waveforms

↓ **FFT**

frequency-domain data

↓

Transmission function

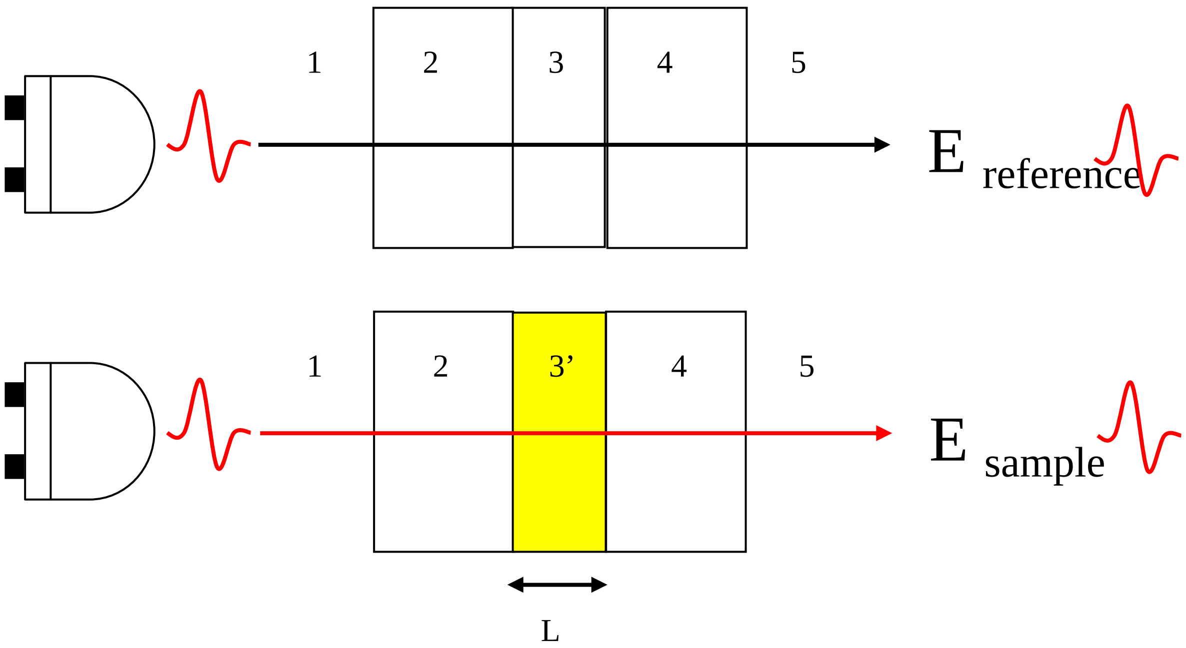
$$T(\omega) = \frac{E_{SAMPLE}(\omega)}{E_{REF}(\omega)}$$

↓

Model of the Material and Numerical method, → ***n, k***

(L. Duvillaret *et al*. IEEE J. Sel Top quantum Electron. 2, 739 (1996))

How to derive n and k from THz-TDS (II)



1: air
2: fused silica
3':sample
3: air
4: fused silica
5: air

Terms considered:

1. transmission and reflection coefficients at a-b interface;

2. propagation coefficient in medium a;

3. Fabry-Perot effect between layers 2 and 4;

a, b: 1-4

How to derive n and k from THz-TDS (III)

$$E_{reference}(\omega) = T_{12}(\omega)P_2(\omega,L)T_{23}(\omega)P_3(\omega,L)T_{34}(\omega)P_4(\omega,L)T_{45}(\omega)\bullet$$

$$\underbrace{\sum_{k=0}^{+\infty}\left[R_{34}(\omega)P_3^2(\omega,L)R_{32}(\omega)\right]^k}_{FP_3(\omega)}\bullet E(\omega)$$

$$E_{sample}(\omega) = T_{12}(\omega)P_2(\omega,L)T_{23'}(\omega)P_{3'}(\omega,L)T_{3'4}(\omega)P_4(\omega,L)T_{45}(\omega)\bullet$$

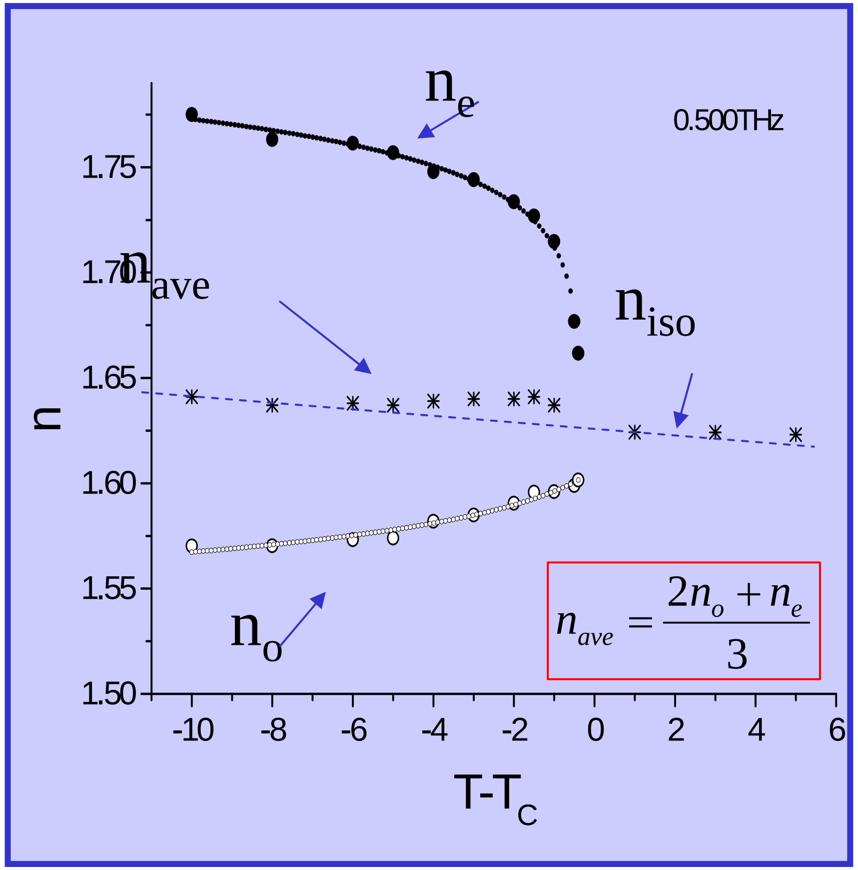
$$\underbrace{\sum_{k=0}^{+\infty}\left[R_{3'4}(\omega)P_{3'}^2(\omega,L)R_{3'2}(\omega)\right]^k}_{FP_{3'}(\omega)}\bullet E(\omega)$$

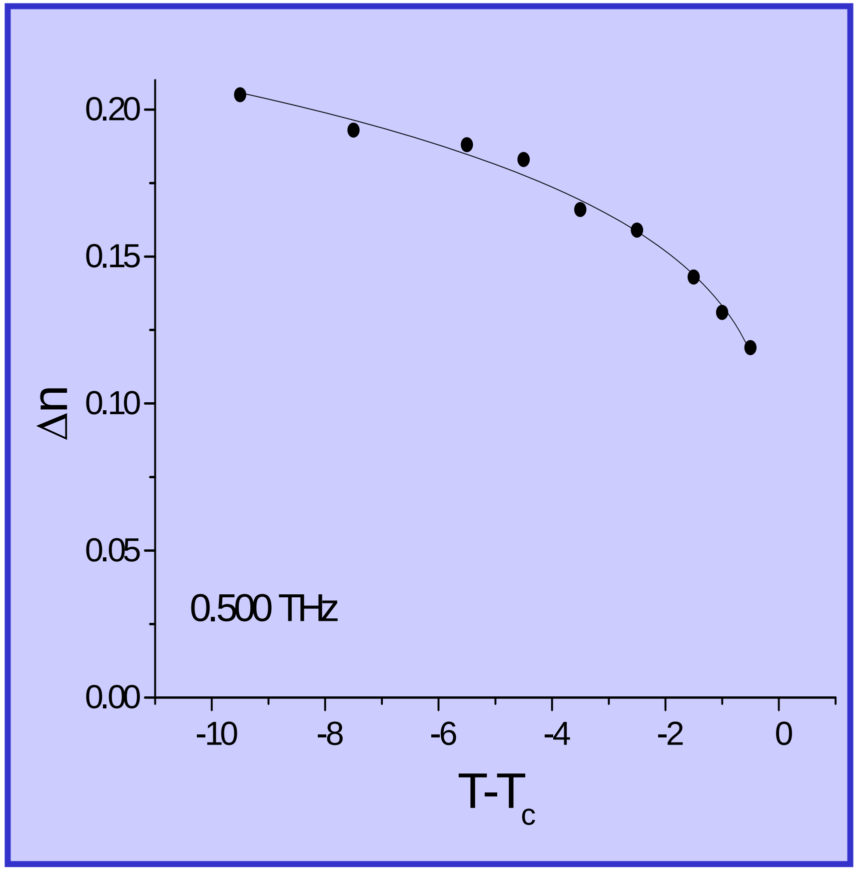
$$T(\omega) = \frac{E_{sample}(\omega)}{E_{reference}(\omega)}$$

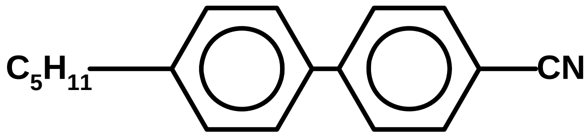
Transmission coefficient

$$= \frac{T_{23'}T_{3'4}}{T_{23}T_{34}}\frac{P_{3'}}{P_3} = \frac{\tilde{n}_{3'}(\tilde{n}_2+1)^2}{(\tilde{n}_2+\tilde{n}_{3'})^2}\times\left[\exp\left(-i\frac{\omega d}{c}(\tilde{n}_{3'}-\tilde{n}_{air})\right)\right]\times FP(\omega)$$

Temperature Dependence of the THz Refractive Indices for 5CB



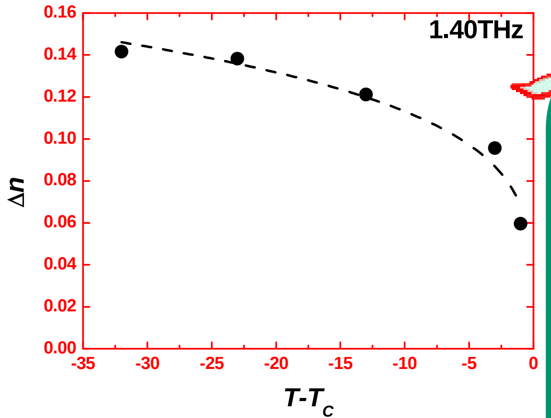


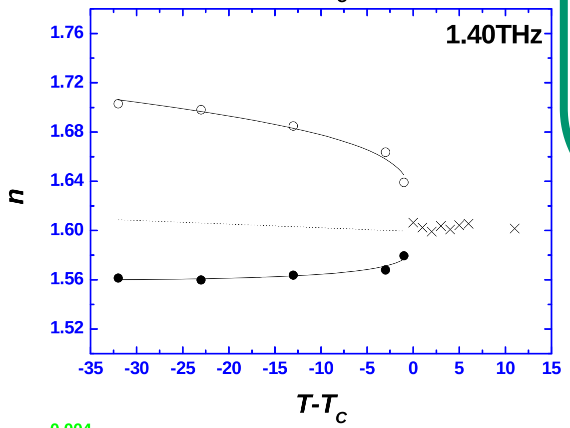


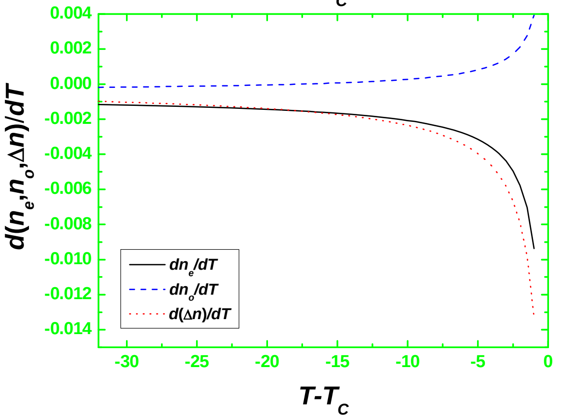
Measured T_c: 34.5℃

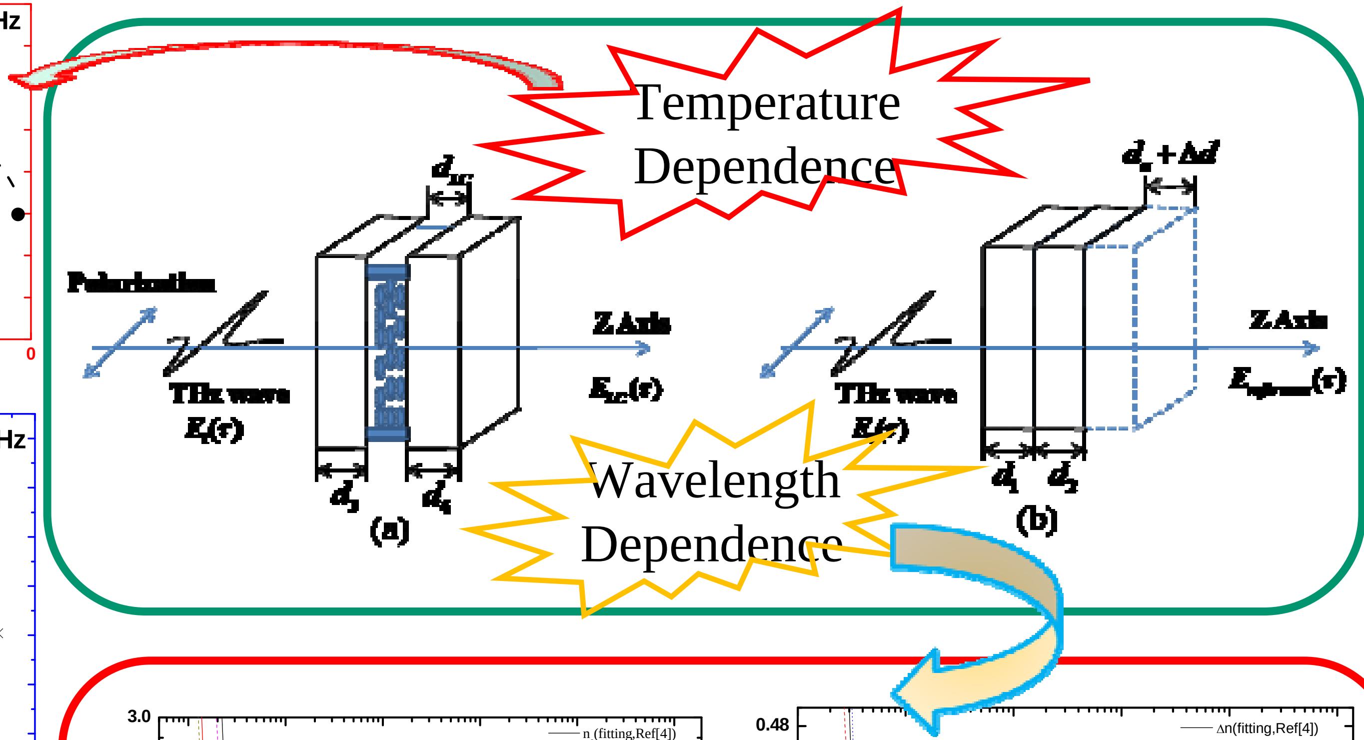
Δn of 5CB: 0.15 ~0.2

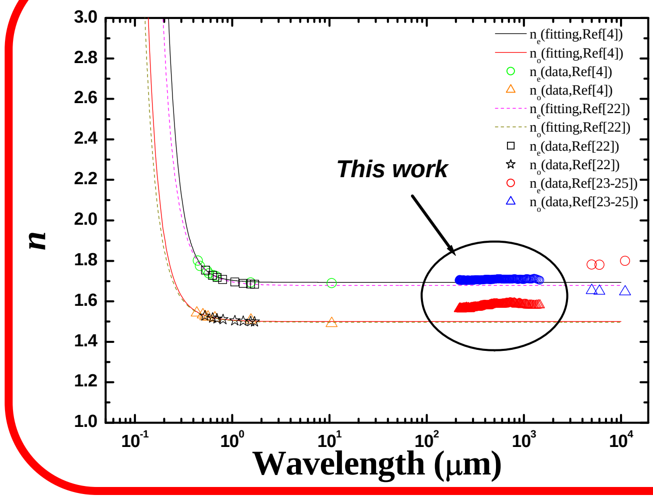
The Complex Refractive Indices of the LC Mixture E7

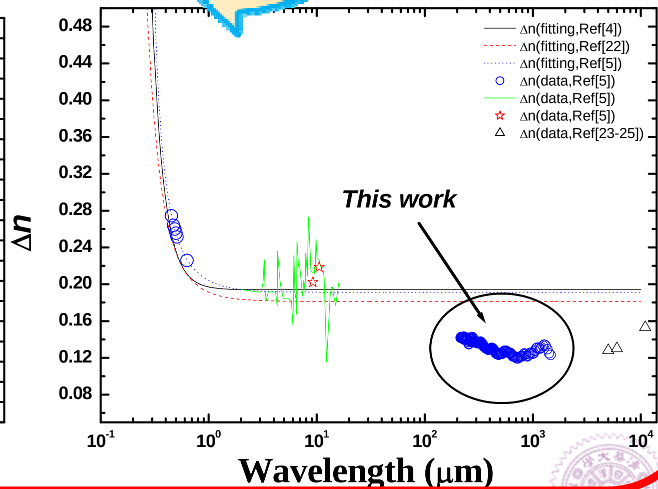






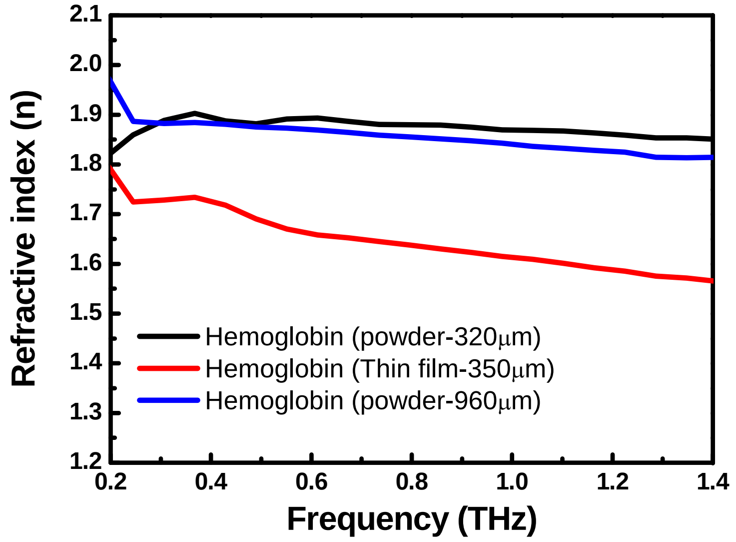


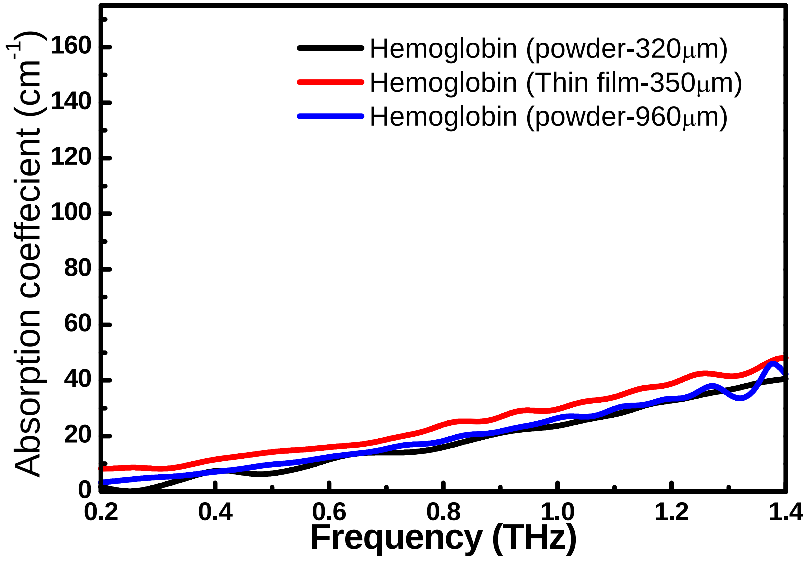




• *J. Opt. Soc. Am. B* (2010)

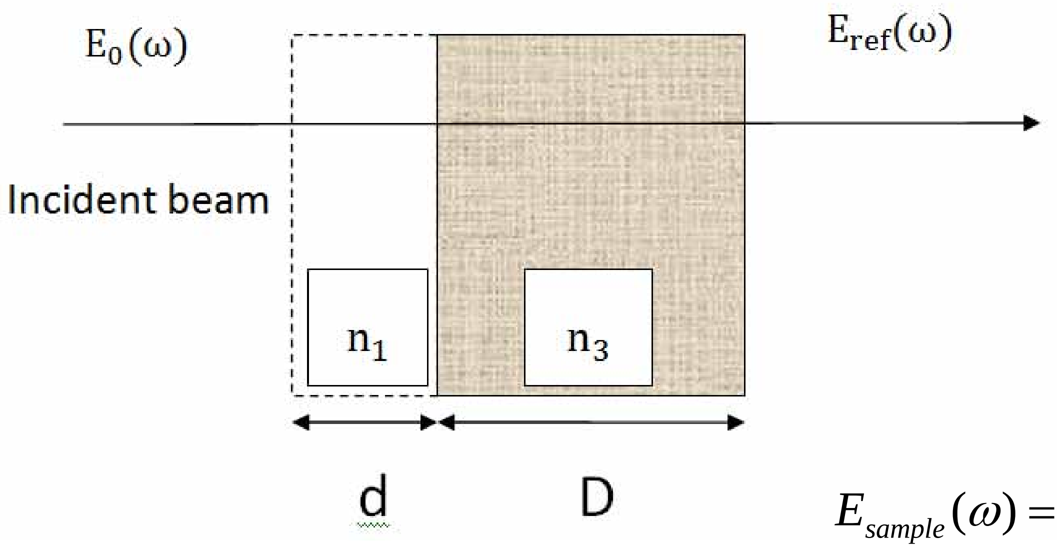
THz Biomedical Sensing:Refractive index and absorption coefficient of deoxyhemoglobin





	Water	Blood	Hemoglobin (powder)	Hemoglobin (Thin film)
Refractive index-mean value (with standard deviation)	~2.04 (0.07)	~2.01 (0.03)	~1.87 (0.02)	~1.61 (0.03)
Absorption coefficient (cm^{-1})	150➔250	120➔240	8➔46	14➔52

Thin-Film and Nano-structures



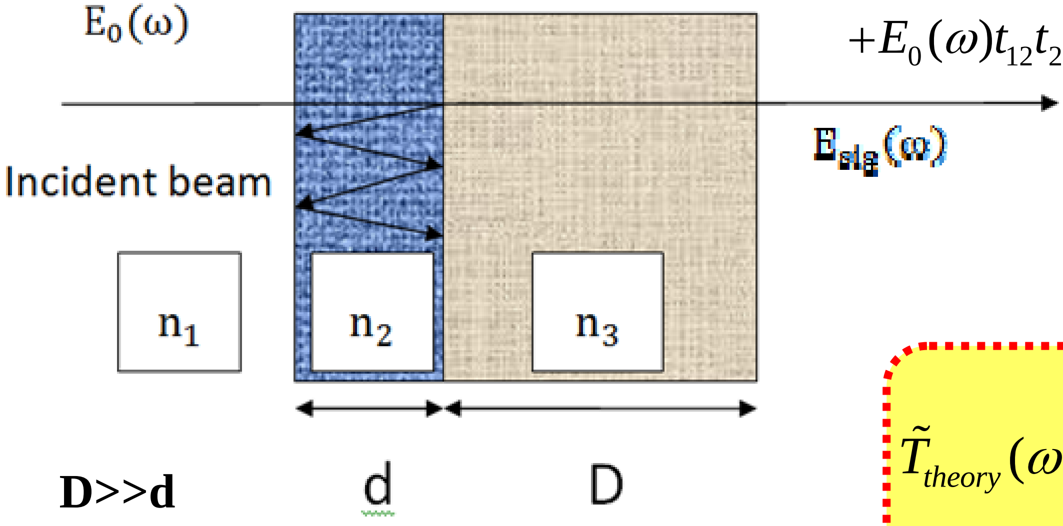
$$t_{ab} = \frac{2n_a}{n_a + n_b} \qquad r_{ab} = \frac{n_a - n_b}{n_a + n_b}$$

$$E_{ref}(\omega) = t_{13}t_{31}E_0(\omega)e^{i\frac{n_1\omega d + n_3\omega D}{c}}$$

$$E_{sig}(\omega) = t_{31}E_{sample}(\omega)e^{i\frac{n_3\omega D}{c}}$$

$$E_{sample}(\omega) = E_0(\omega)t_{12}t_{23}e^{i\frac{n_2\omega d}{c}} + E_0(\omega)t_{12}t_{23}r_{21}r_{23}e^{i\frac{3n_2\omega d}{c}}$$

$$+E_0(\omega)t_{12}t_{23}r_{21}^2r_{23}^2e^{i\frac{5n_2\omega d}{c}} + \cdots + E_0(\omega)t_{12}t_{23}r_{21}^q r_{23}^q e^{i\frac{(2q+1)n_2\omega d}{c}}$$



D>>d

$$E_{sample} = E_0(\omega)\frac{t_{12}t_{23}e^{i\frac{n_2\omega d}{c}}}{1 - r_{12}r_{23}e^{i\frac{2n_2\omega d}{c}}}$$

$$\tilde{T}_{theory}(\omega) = \frac{E_{sig}(\omega)}{E_{ref}(\omega)} = \frac{t_{12}t_{23}e^{i\frac{(\tilde{n}_2-1)\omega d}{c}}}{t_{13}(1 - r_{21}r_{23}e^{2i\frac{\tilde{n}_2\omega d}{c}})}$$

Extraction of Electrical Characteristics by THz-TDS

Sample TDS signal

Reference TDS signal

FFT → Complex Transmittance

Theoretical Transmittance

→ Complex refractive index

$$\tilde{\varepsilon}(\omega) = \varepsilon_\infty - i\frac{\tilde{\sigma}(\omega)}{\omega\varepsilon_0}$$

$$\sigma(\omega) = \frac{\varepsilon_0\omega_p^2\tau}{1-i\omega\tau}\left(1+\frac{c}{1-i\omega\tau}\right)$$

Drude-Smith model

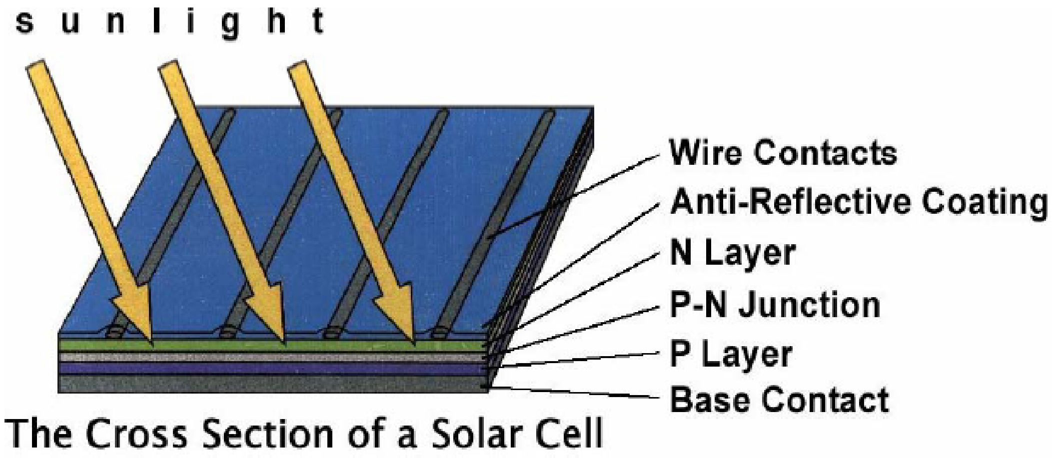
Complex refractive index → Complex conductivity → Plasma frequency, Carrier scattering time

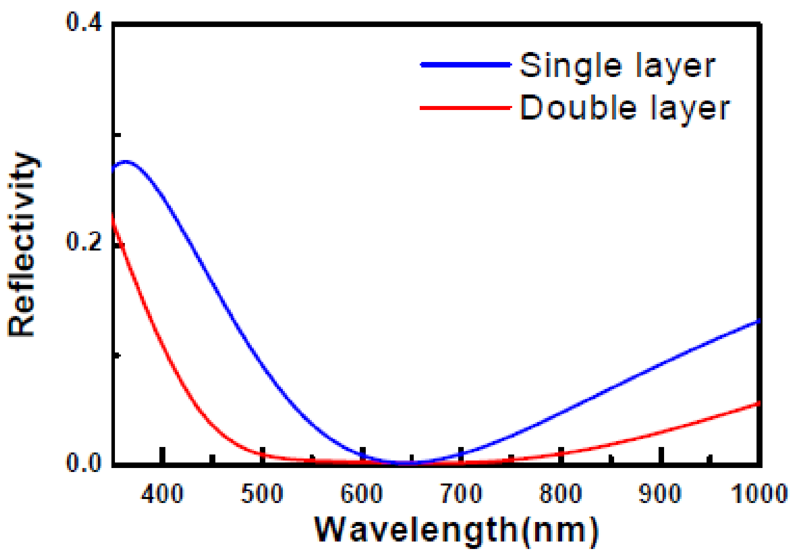
Plasma frequency, Carrier scattering time → Mobility & Carrier Concentration

$$\mu = (1+c)e\tau / m^*$$

$$\omega_P^2 = e^2 N_C / (m^*\varepsilon_0)$$

Anti-reflection layer in Photovoltaics



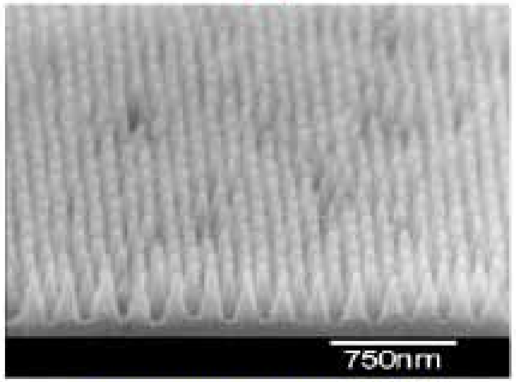


- Carrier collection vs Photon collection
- Tradeoff between area covered by *metal electrode* and *AR coating*
- Conventional dielectric AR coating is neither *omnidirectional*, nor *broadband*.

Nanostructured AR Surface

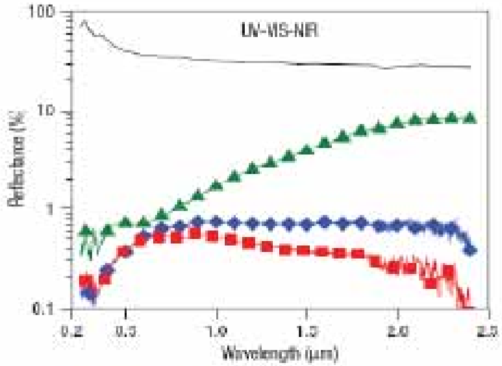
- Moth-eye structures
  - Omnidirectional and broadband AR (<5%) due to a *graded refractive-index profile*
  - E-beam lithography required
  - High cost for large area fabrication
- Advanced nanostructured AR-coating

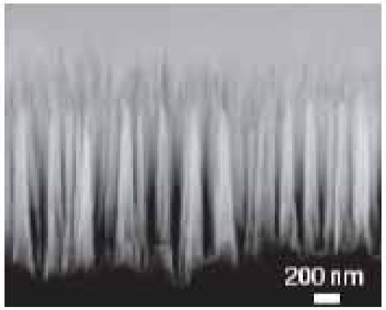
Si nano-pyramids



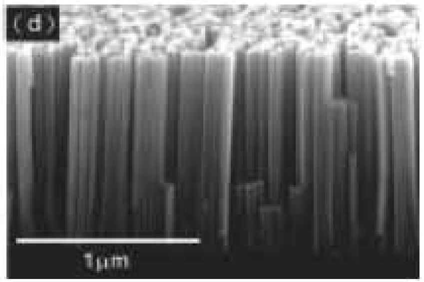
Opt. Lett. 24,20(1999)

- Top-down (dry/wet etch)
- Bottom-up (Epi/ deposition)

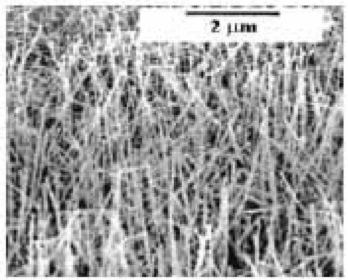




Nature Nanotech. 2, 770 (2007)



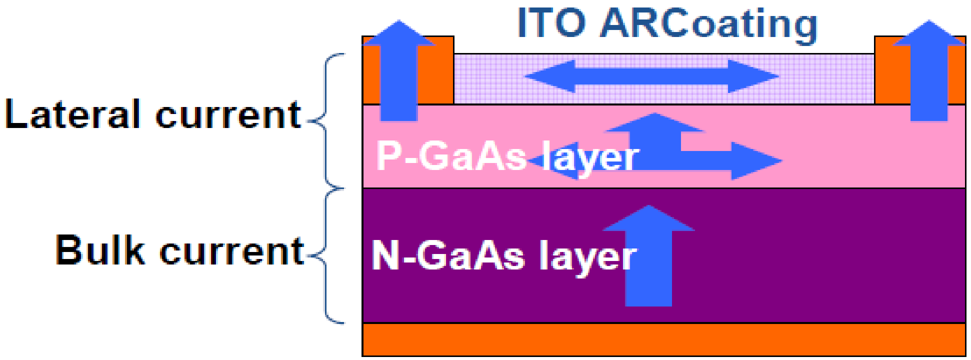
Appl. Phys. Lett. 89,243105 (2006)

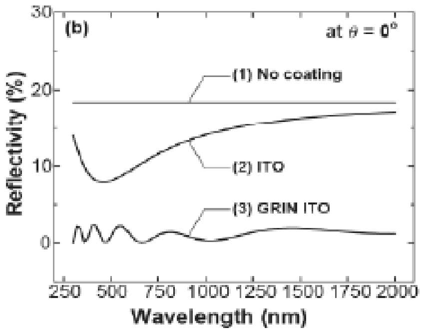


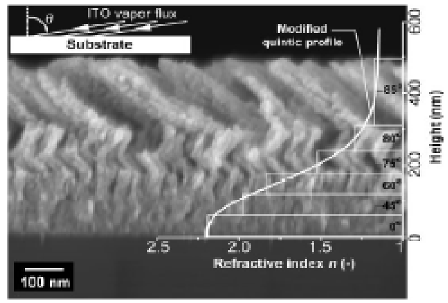
Appl. Phys. Lett. 83, 996 (2003)

- Nanostructured ITO AR layer to enhance both photon absorption and carrier collection!

Nanostructured ITO AR layer







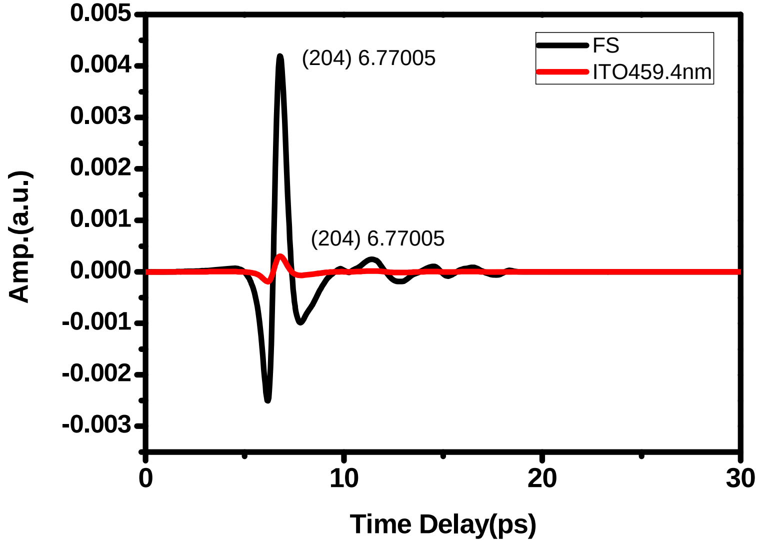
Adv. Mater., 20, 801, 2008.

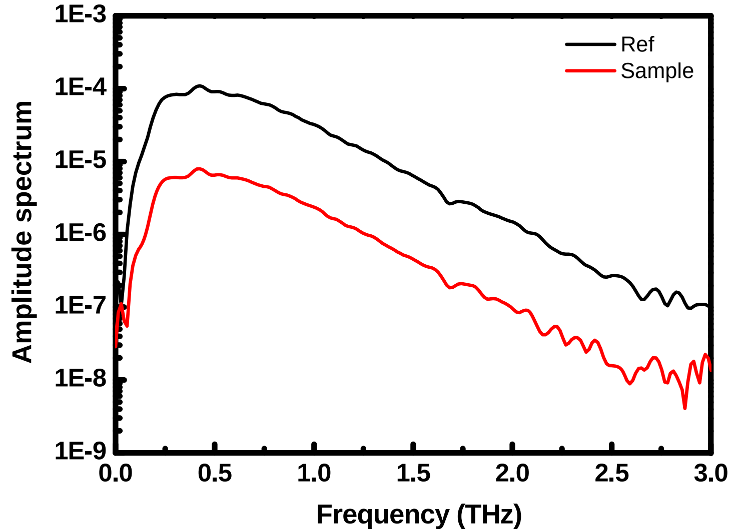
- ITO films:
  - Low resistivity ,~2╳10^{-4} Ω-cm
  - Transparency-Good: ~80% - 90%
  - Widely used in LEDs, solar cells.

- ITO nano-columns:
  - Bottom-up method
  - Conductivity (acceptable)
  - Superior AR

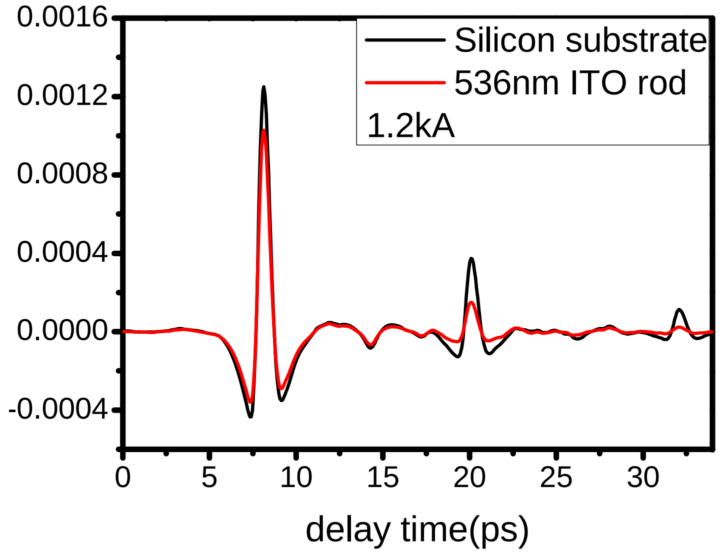
• Nanostructured ITO AR layer to enhance both photon collection and carrier collection!

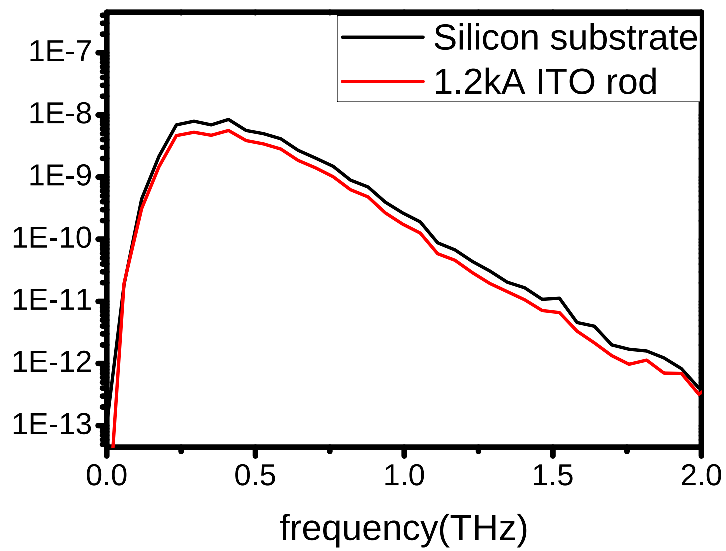
THz Waveforms and Spectra





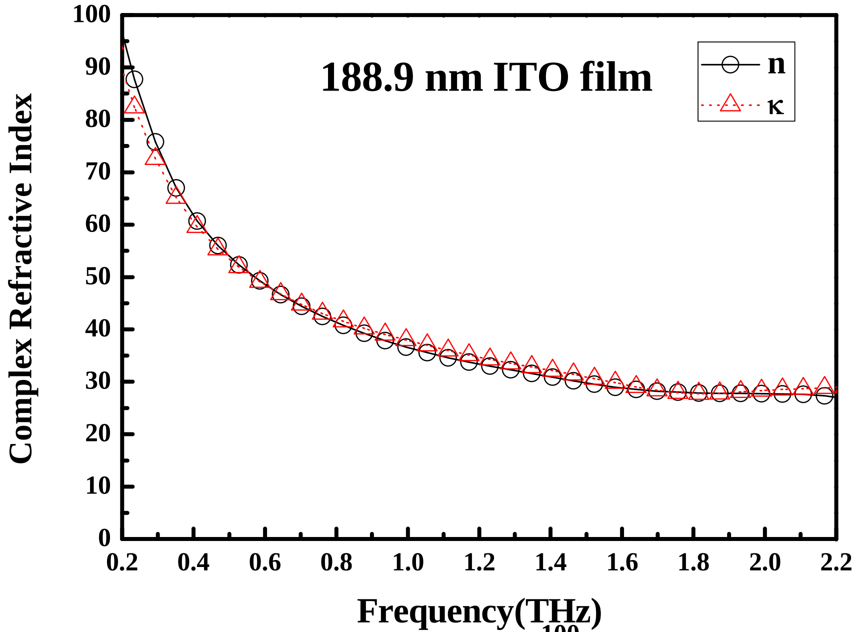
ITO
Film

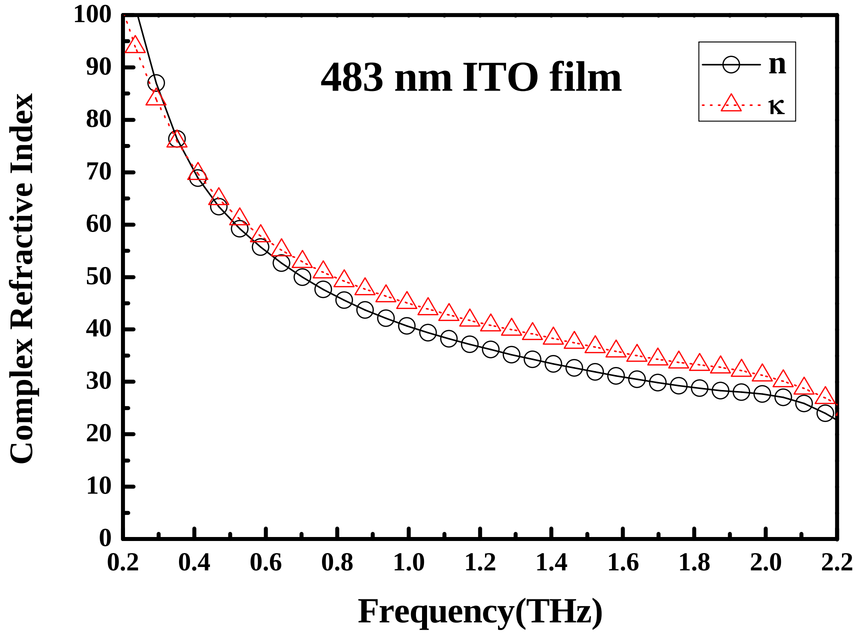


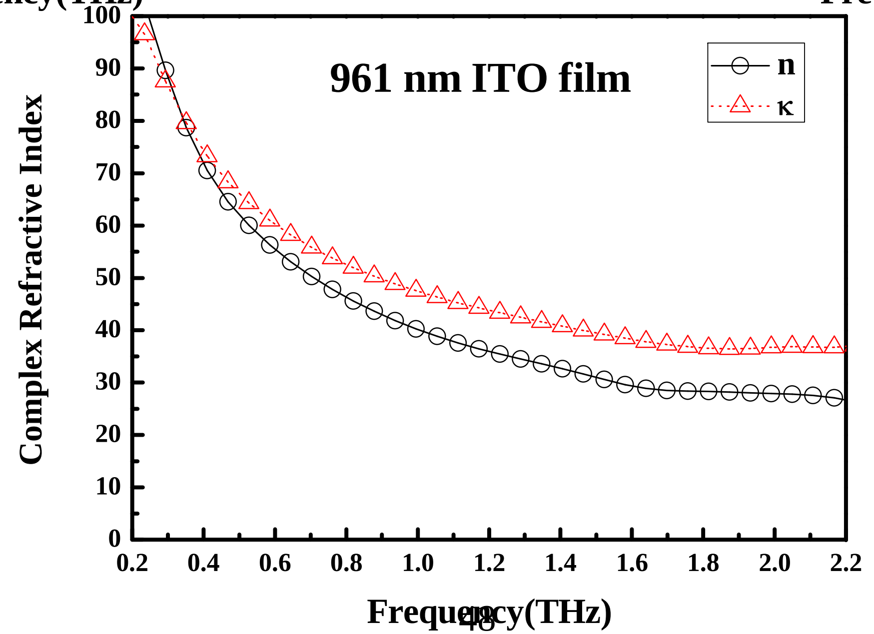


ITO
Whisker

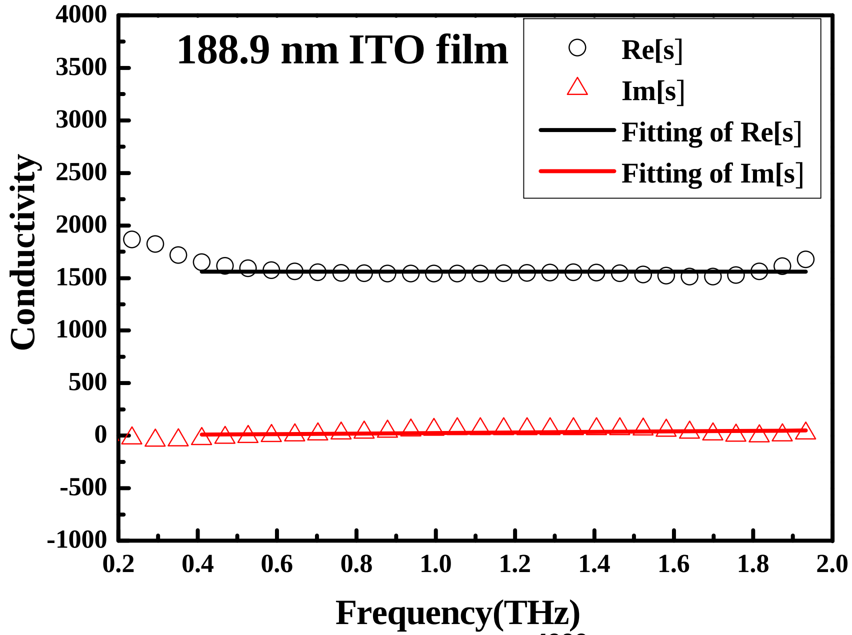
ITO thin film - refractive index

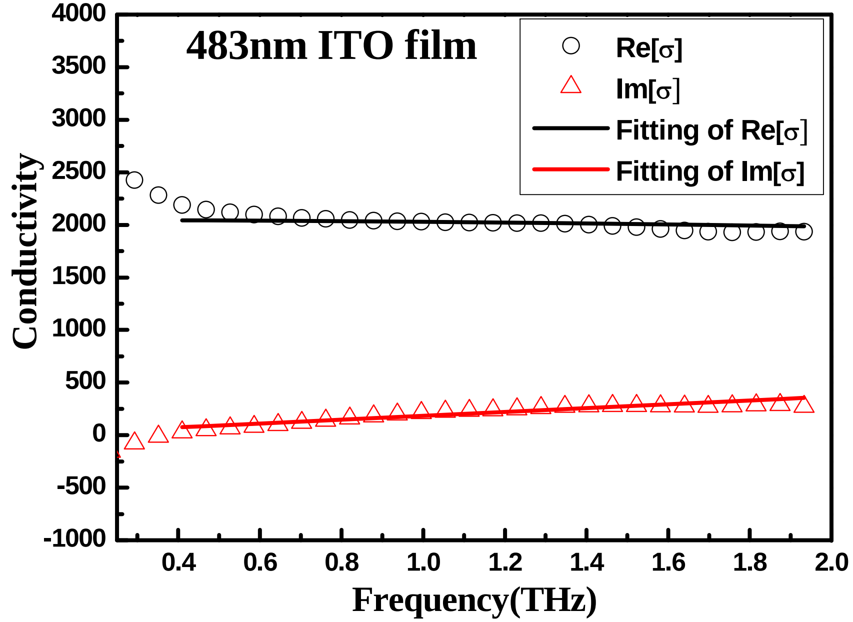


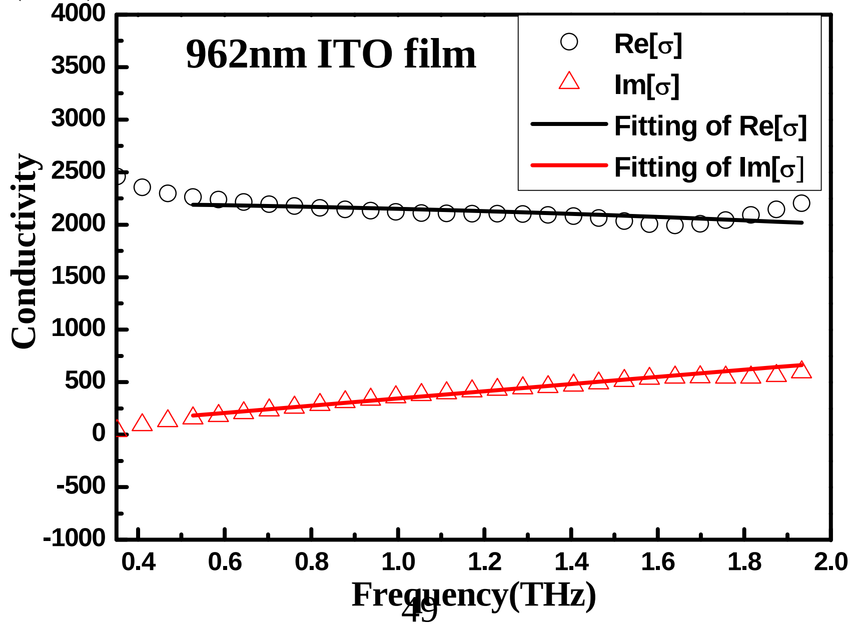




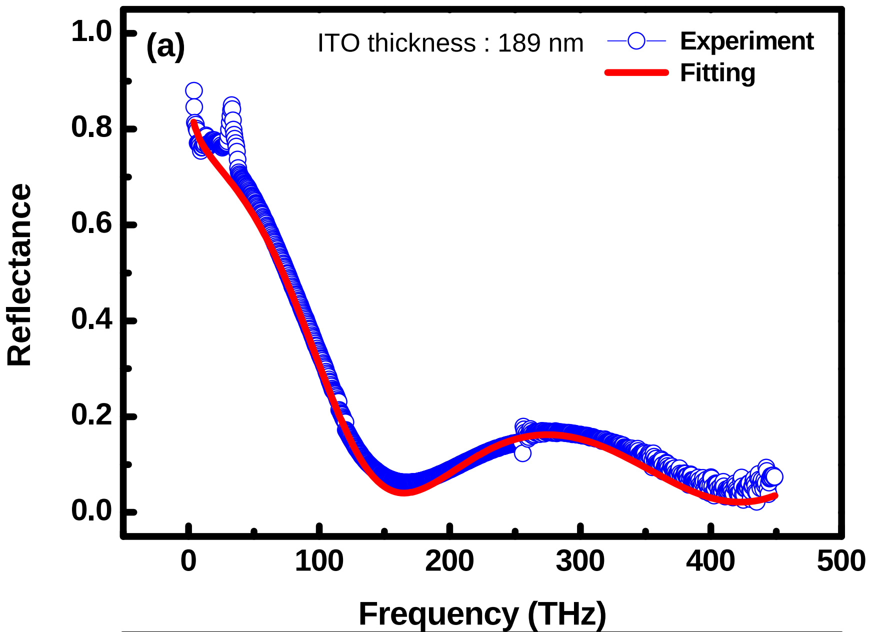
ITO thin film - conductivity

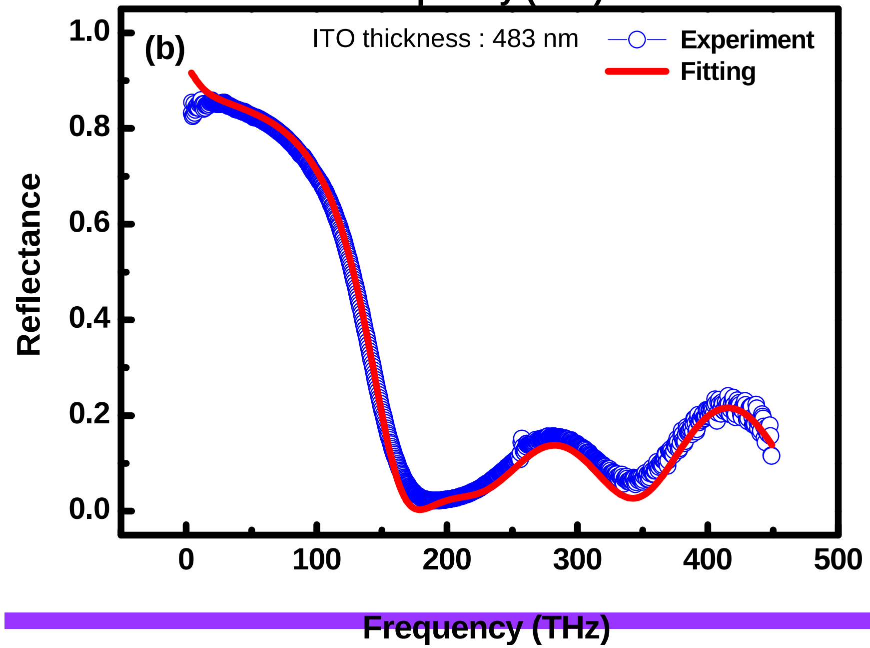


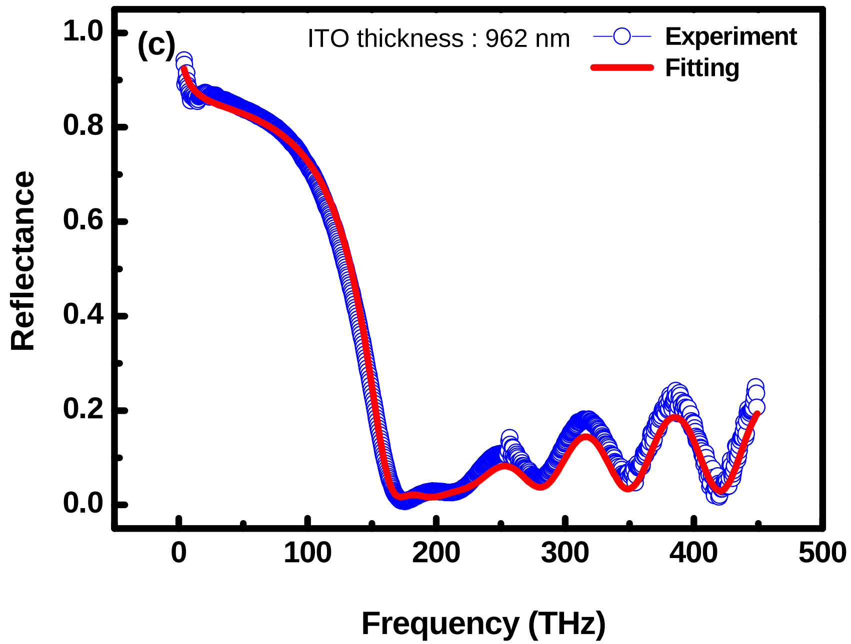




ITO thin film – FTIR reflectance







ITO thin film – Electrical Properties

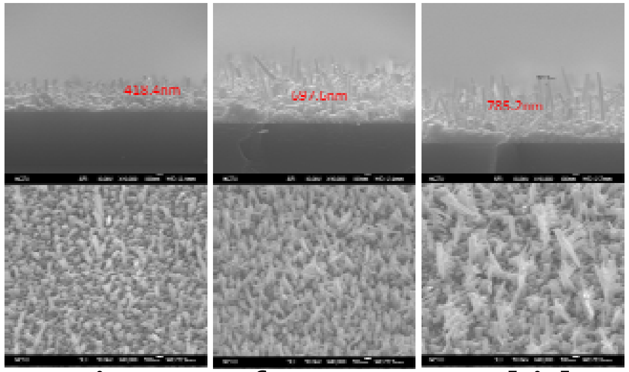
ITO Film THz-TDS	ω_p (rad·THz)	τ (fs)	μ (cm^2/Vs)	n (cm^{-3}) $\times 10^{20}$	σ ($\Omega^{-1}cm^{-1}$)
189nm	1590	6.8	34.2	2.79	1525
483nm	1860	6.7	33.7	3.81	2052
962nm	1930	6.5	32.7	4.10	2142

ITO Film FTIR	ω_p (rad·THz)	τ (fs)	μ (cm^2/Vs)	n (cm^{-3}) $\times 10^{20}$	σ ($\Omega^{-1}cm^{-1}$)
189nm	1600	6.9	34.7	2.82	1566
483nm	1850	6.6	33.2	3.77	2000
962nm	1940	5.8	29.1	4.14	1930

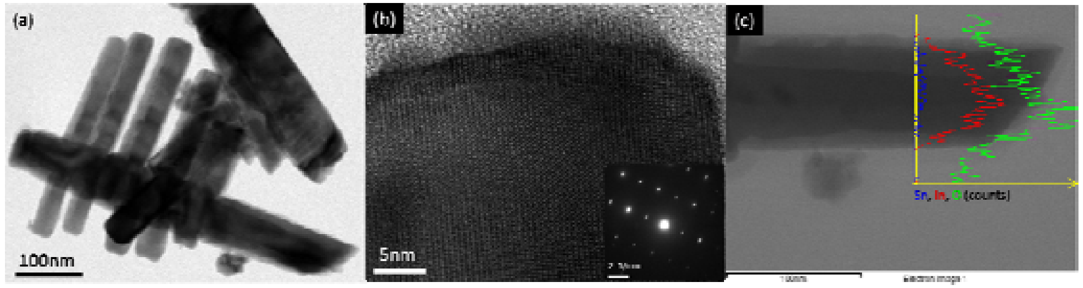
ITO thin film – Optical vs Hall Studies

THz-TDS	**ω_p (rad·THz)**	**τ (fs)**	**μ (cm^2/Vs)**	**n (cm^{-3})**	**σ ($\Omega^{-1}cm^{-1}$)**
189 nm	1590	6.8	34.2	2.79×10^{20}	1525
483 nm	1860	6.7	33.7	3.81×10^{20}	2052
962 nm	1930	6.5	32.7	4.10×10^{20}	2142
FTIR	**ω_p (rad·THz)**	**τ (fs)**	**μ (cm^2/Vs)**	**n (cm^{-3})**	**σ ($\Omega^{-1}cm^{-1}$)**
189 nm	1600	6.9	34.7	2.82×10^{20}	1566
483 nm	1850	6.6	33.2	3.77×10^{20}	2000
962 nm	1940	5.8	29.1	4.14×10^{20}	1930
Hall	**ω_p (rad·THz)**	**τ (fs)**	**μ (cm^2/Vs)**	**n (cm^{-3})**	**σ ($\Omega^{-1}cm^{-1}$)**
189 nm			38.4	2.5×10^{20}	1557
483 nm			38.0	3.4×10^{20}	2045
962 nm			34.3	4.1×10^{20}	2250

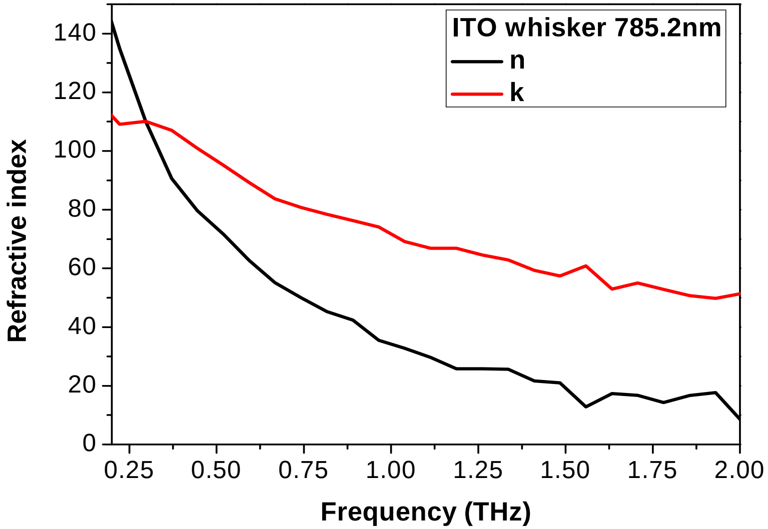
THz studies of ITO Nanostructures

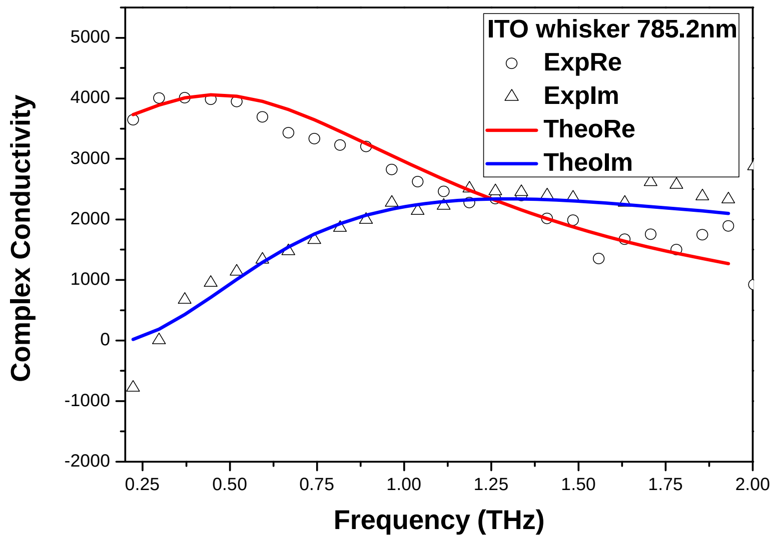


SEM images of ITO Nano-whiskers



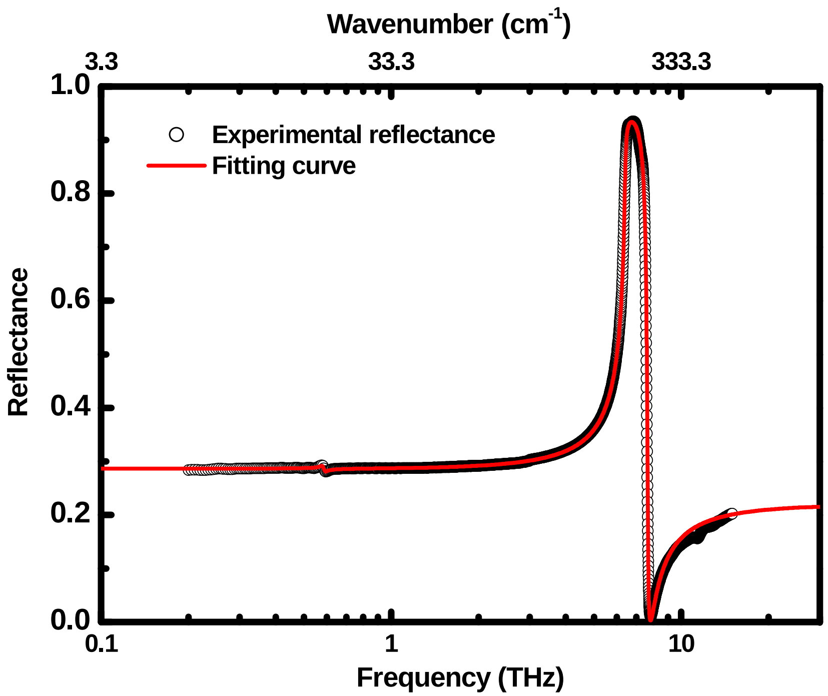
The TEM characterizations of ITO Nano-whiskers

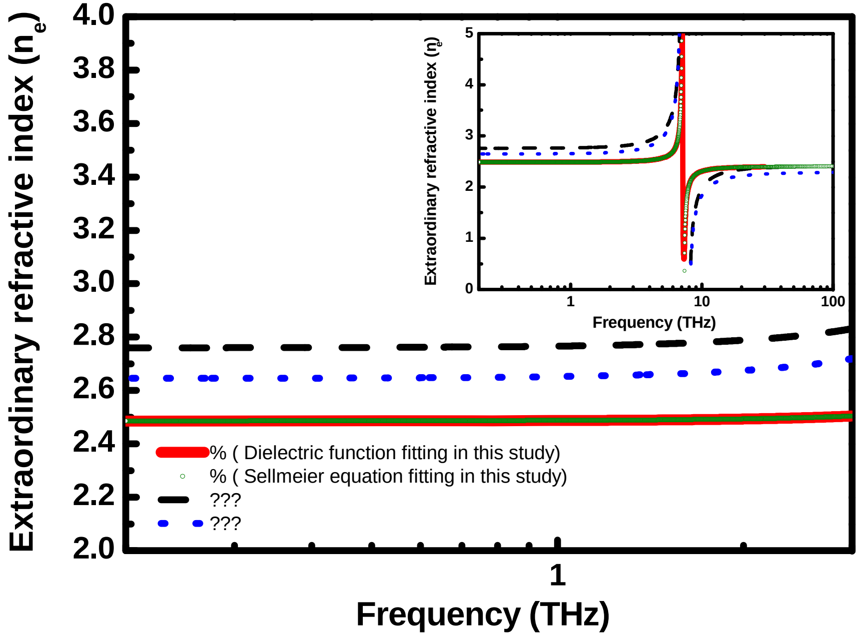




Thickness(nm)	ω_p ($rad\text{-}THz$)	τ (fs)	C	Conductivity @ 1THz ($\Omega^{-1}cm^{-1}$) Exp/Fit	Eletron density (cm^{-3})	Mobility ($cm^2V^{-1}s^{-1}$)
785.2	614	221.7	-0.544	2621/2853	$3.56*10^{19}$	593

Dielectric function of GaSe





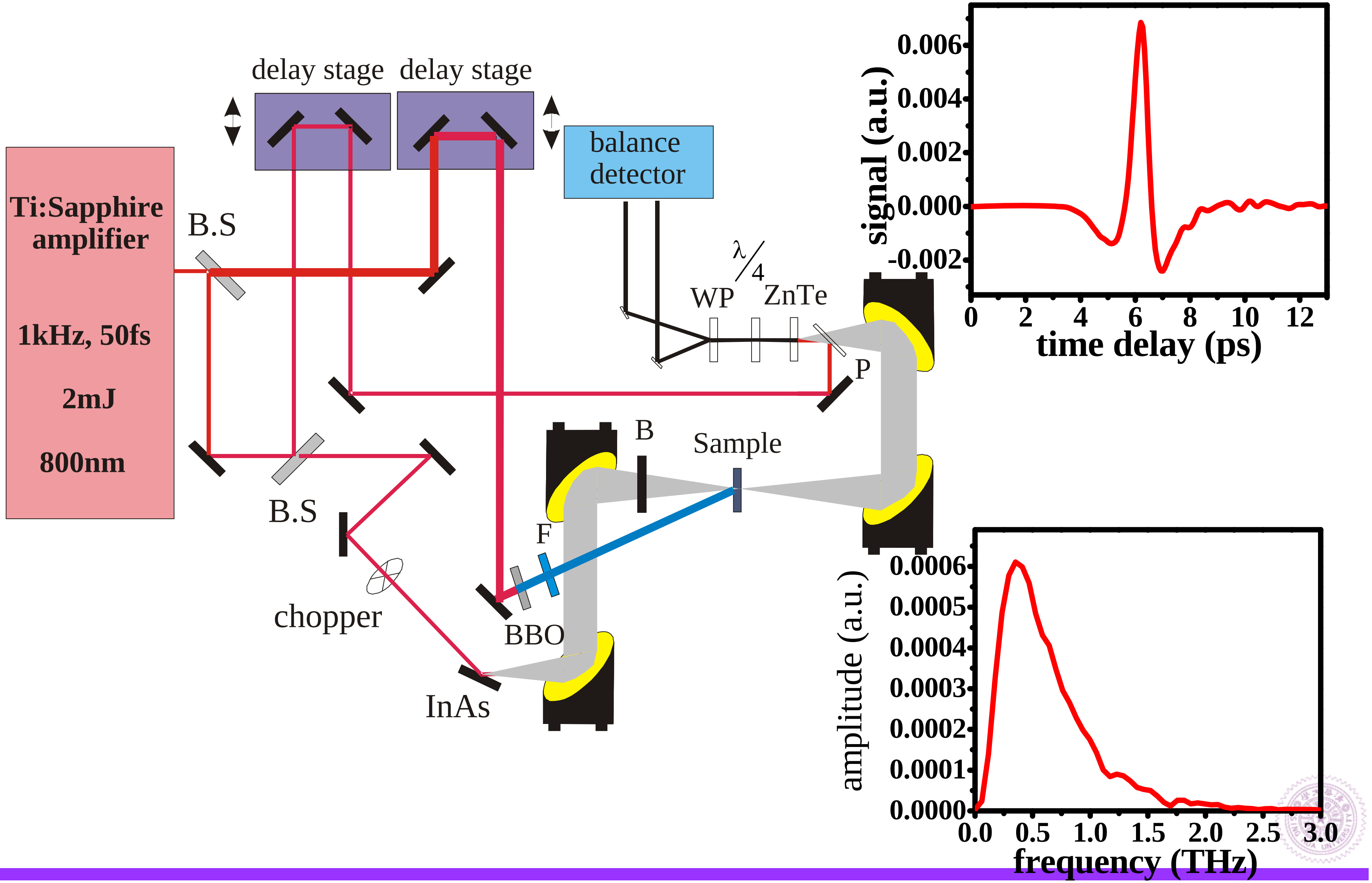
$$\varepsilon_o(\omega) = A\omega^6 + B\omega^4 + C\omega^2 + S_1 + \frac{(\omega_L^2 - \omega_T^2)S_1}{\omega_T^2 - \omega^2 - i\Gamma_1\omega} + \frac{\omega_t^2 S_2}{\omega_t^2 - \omega^2 - i\Gamma_2\omega}$$

$$\varepsilon_e(\omega) = A'\omega^6 + B'\omega^4 + C'\omega^2 + S_3 + \frac{(\omega_L^2 - \omega_T^2)S_3}{\omega_T^2 - \omega^2 - i\Gamma_3\omega}$$

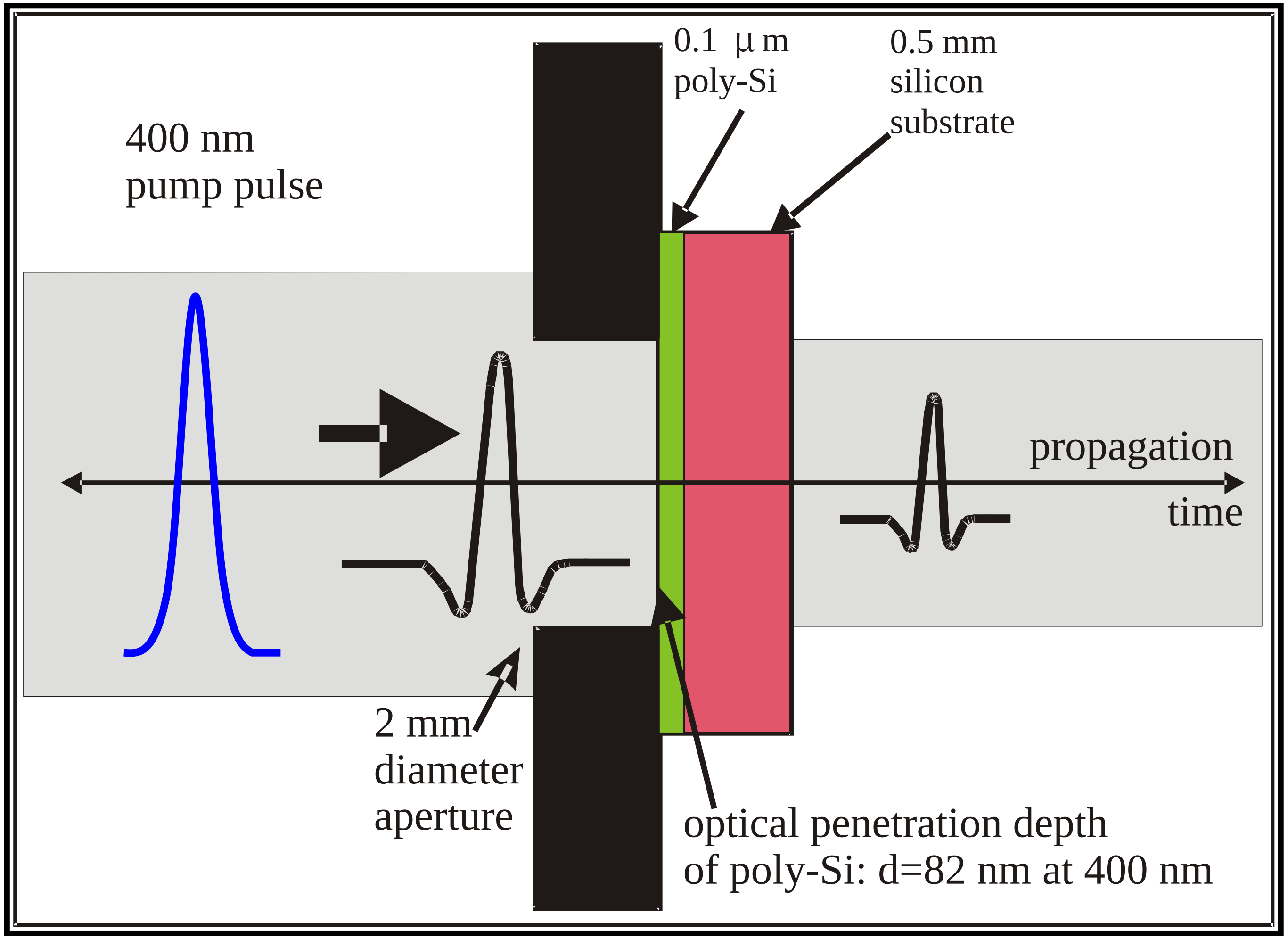
where A=6.105$\times$10^{-27} cm^6, B=1.8564$\times$10^{-18} cm^4, C=4.0499$\times$10^{-9} cm^2, S_1=7.37, S_2=0.017, Γ_1=2.8cm^{-1}, Γ_2=0.5667cm^{-1}, ω_L=255cm^{-1}, ω_T=213.5cm^{-1}, ω_t=19.53cm^{-1}.

where A'=122.3$\times$10^{-27} cm^6, B'=−22.88$\times$10^{-18} cm^4, C'=3.879$\times$10^{-9} cm^2, S_3=5.76, Γ_3=2.8 cm^{-1}, ω_L=245.5 cm^{-1}, ω_T=237 cm^{-1}.

Optical-Pump THz Probe Spectroscopy



Optical Pump Terahertz Probe Spectroscopy

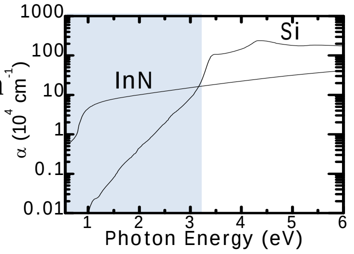


Differential transmission, $\Delta T / T_0 = (T - T_0) / T_0$

InN as efficient THz emitter and its THz spectroscopy

InN

- Eg ~ 0.7 eV
- Wide absorption spectra
- High mobility



Challenges for semiconductor-based THz emitter

- Power loss due to total internal reflection at the interface
- Improvement of light extraction from emitter

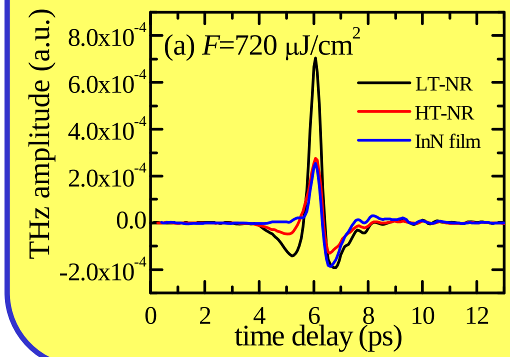
Solution

- Nanostructured emitter
- Rotation of surface electric field

Prof. H. Ahn
Prof. C.-L. Pan

THz emission from nanostructures

H. Ahn, et al., APL 91, 132108 (2007)

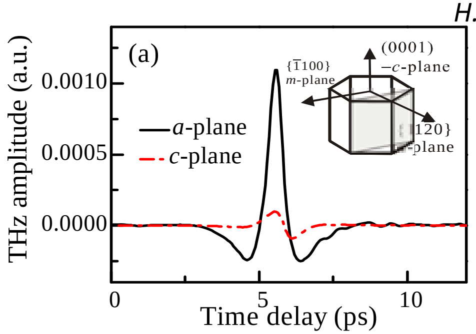


Increase of absorption/emission surface in nanostructure

10 times of power enhancement from nanostructured InN

THz emission from nonpolar InN

H. Ahn, et al., APL 92, 102103 (2008)

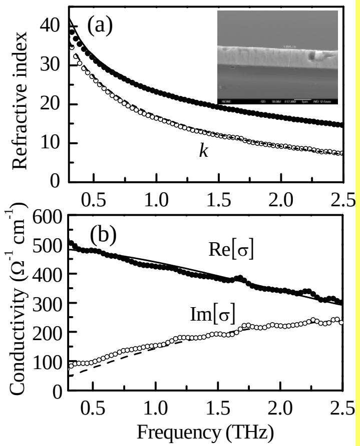


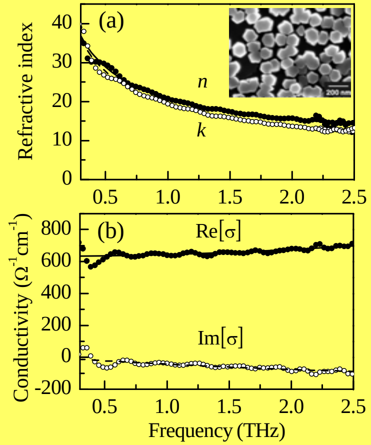
Rotation of dipole oscillation for efficient light extraction

100 times of power enhancement from a-plane InN compared to c-plane InN

THz spectroscopy of InN

H. Ahn, et al., APL 91, 163105 (2007)





Conductivity of nanostructured material cannot be described by the Drude model..

InN epilayer

Drude model

$$\sigma(\omega) = \frac{\varepsilon_0 \omega_p^2 \tau_0}{1 - i\omega\tau_0}$$

InN nanorod

Non-Drude (Drude-Smith) model

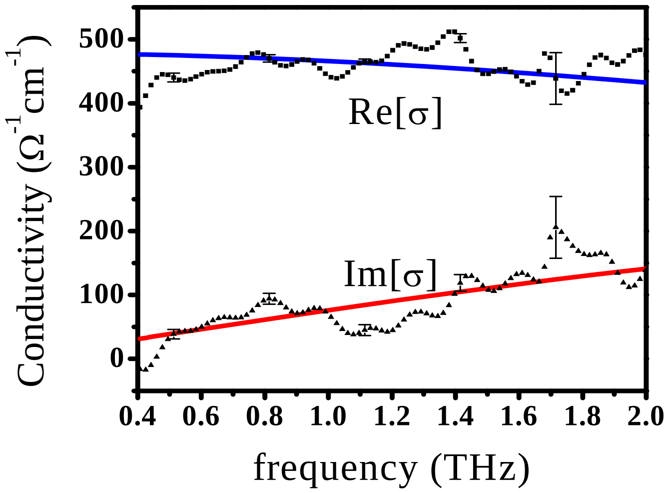
$$\sigma(\omega) = \frac{\varepsilon_0 \omega_p^2 \tau_0}{1 - i\omega\tau_0}\left[1 + \frac{c}{1 - i\omega\tau_0}\right]$$

c<0 for nanorods due to backscattering of electrons

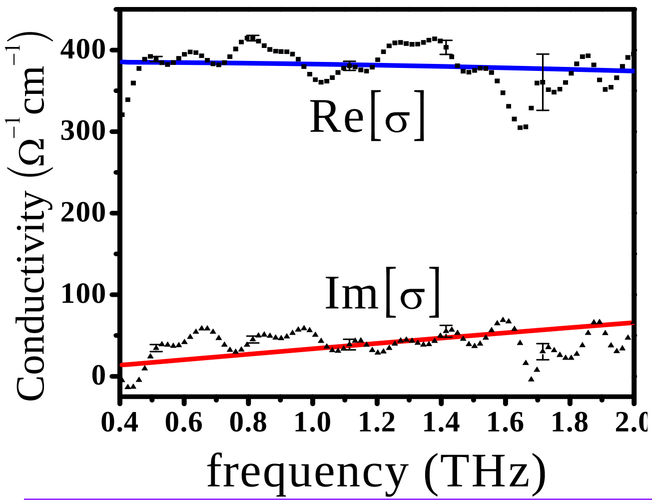
Optical-Pump-Terahertz-Probe studies of femtosecond-laser annealed a-Si

Fitting with Drude model

Grain size : 500 nm



Grain size : 50 nm



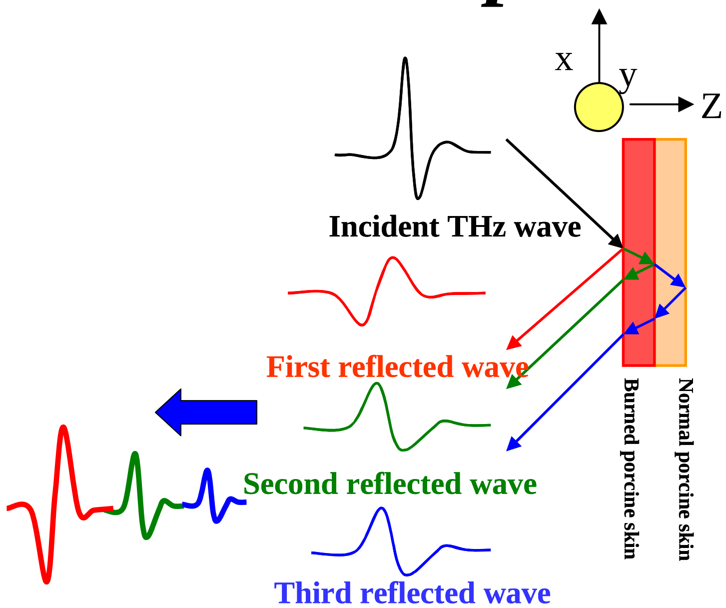
Sample	Average grain size (nm)	mobility (cm^2/Vs)	Plasma frequency (10^{13} Hz)
Bulk-Si (Hall measurement)		158-299	
Bulk-Si (THz-TDS)		162±6.5	8.29±0.21
Poly-Si with large grain size	~ 500	175±19.4	7.26±0.36
Poly-Si with small grain size	~ 50	94.5±20.2	7.20±0.04

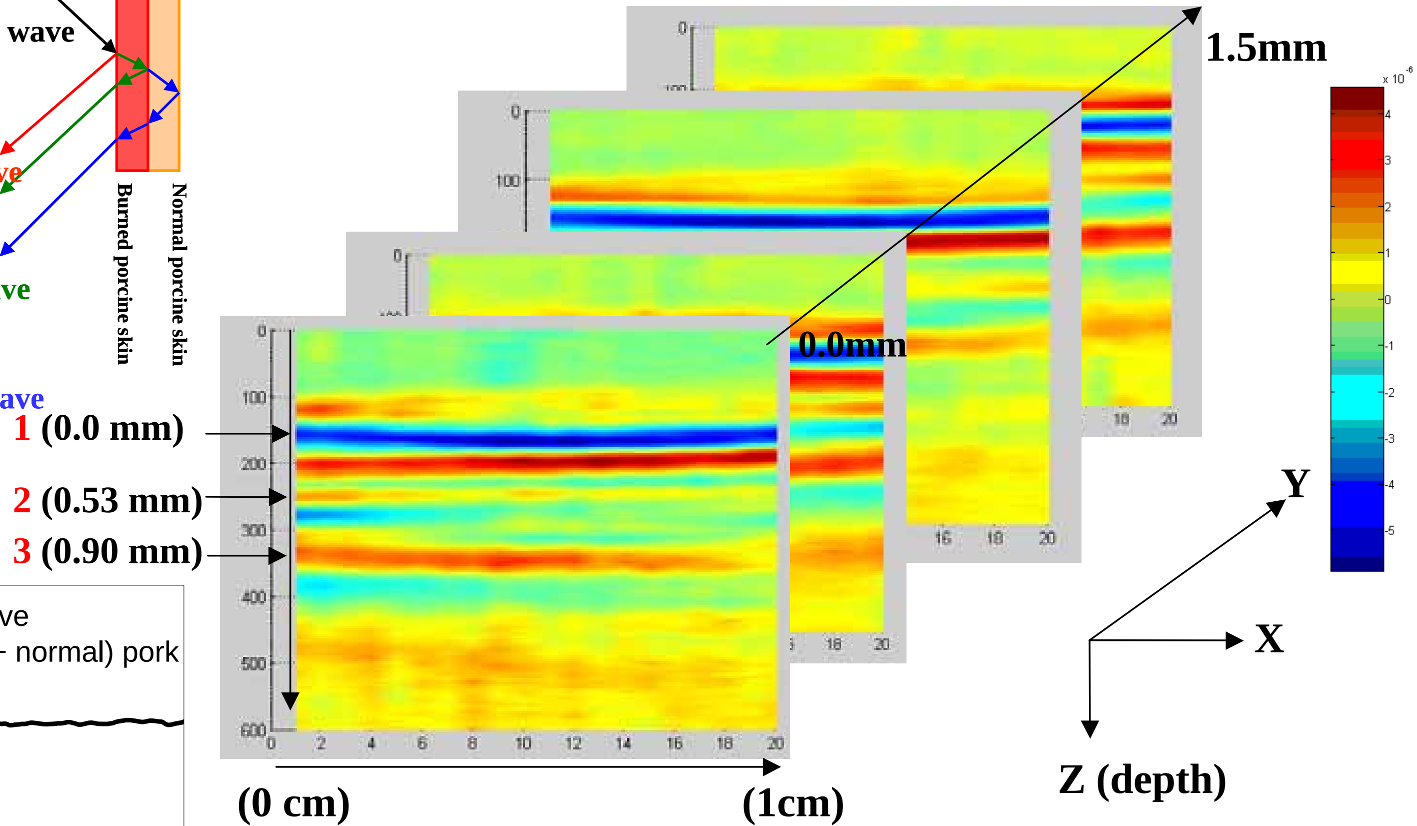
- » The mobility measured by THz-TDS is in good agreement with electrical Hall effect measurement result.
- » OPTP and THz-TDS are effective techniques to differentiate annealed quality of polycrystalline silicon.

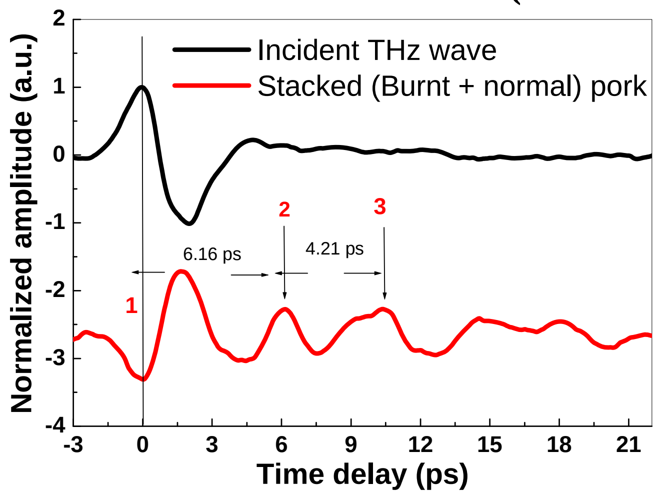
Appl. Phys. B, Sept. 2009

Burn-depth detection with T-ray technology

In collaboration w/ITRI

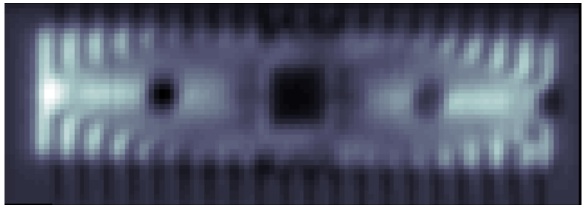


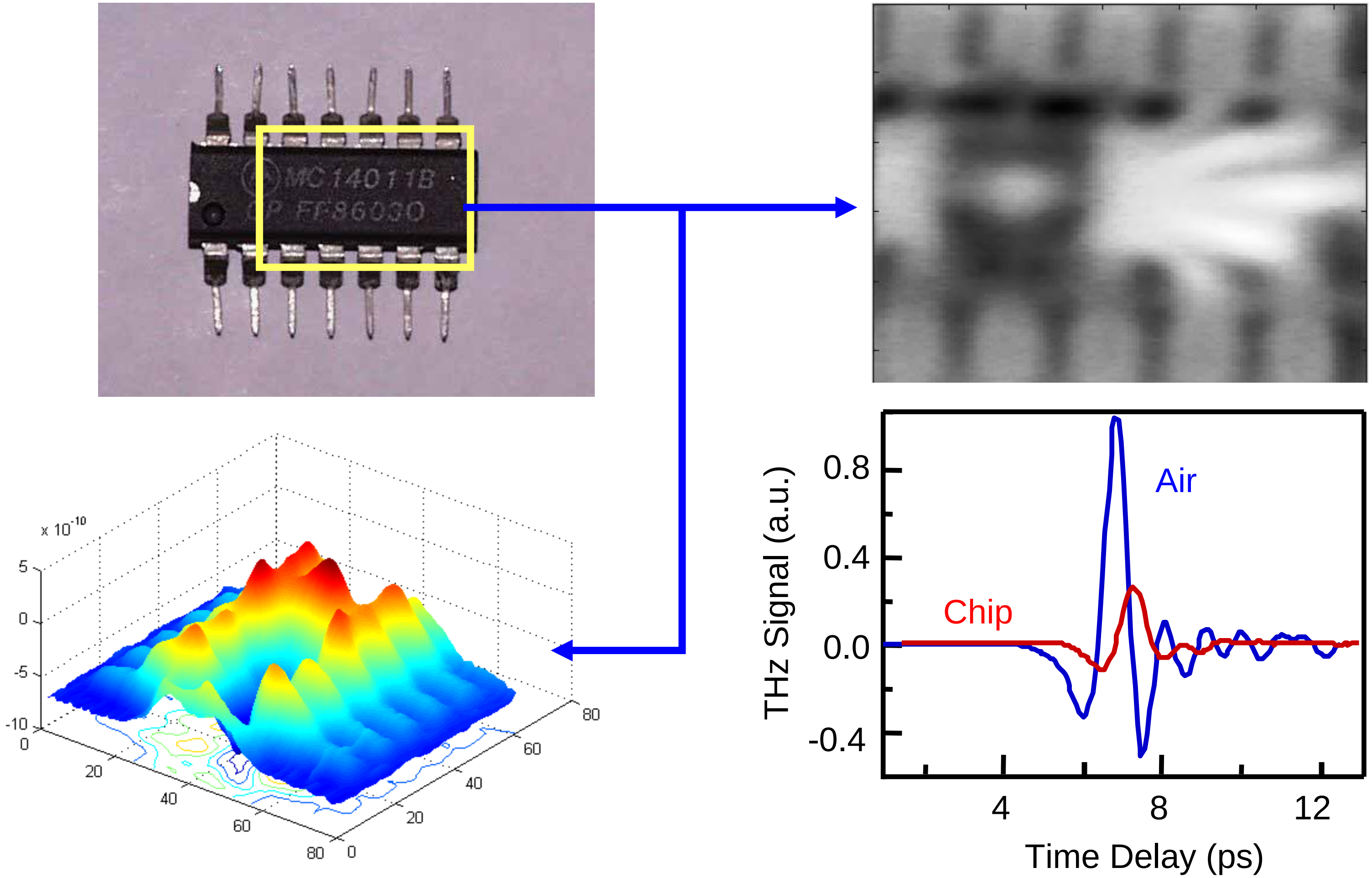




Burnt depth of 0.53mm is resolved via THz imaging , Taiwan patent I276425, U.S. Patent allowed on Aug. 3, 2007

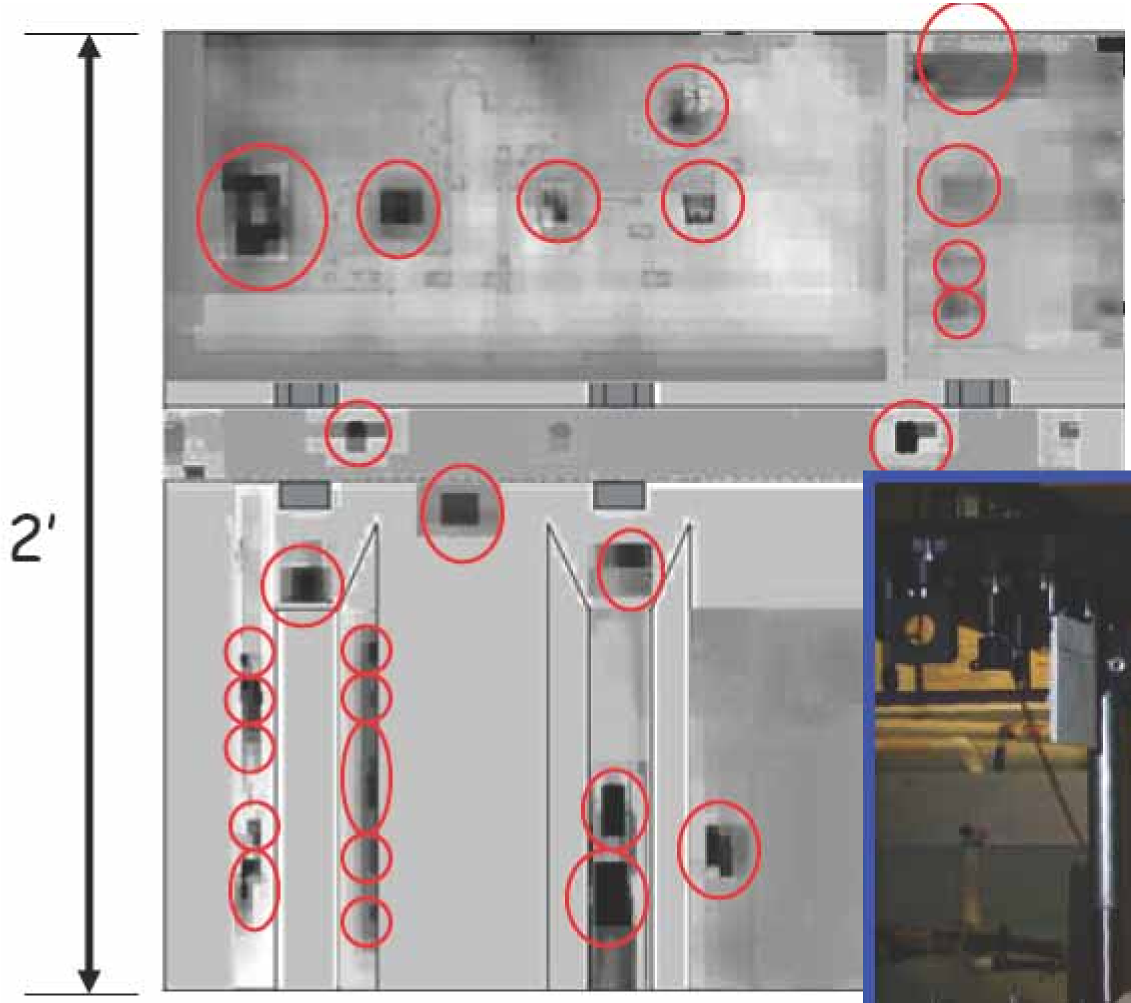
THz Image of a Motorola Chip





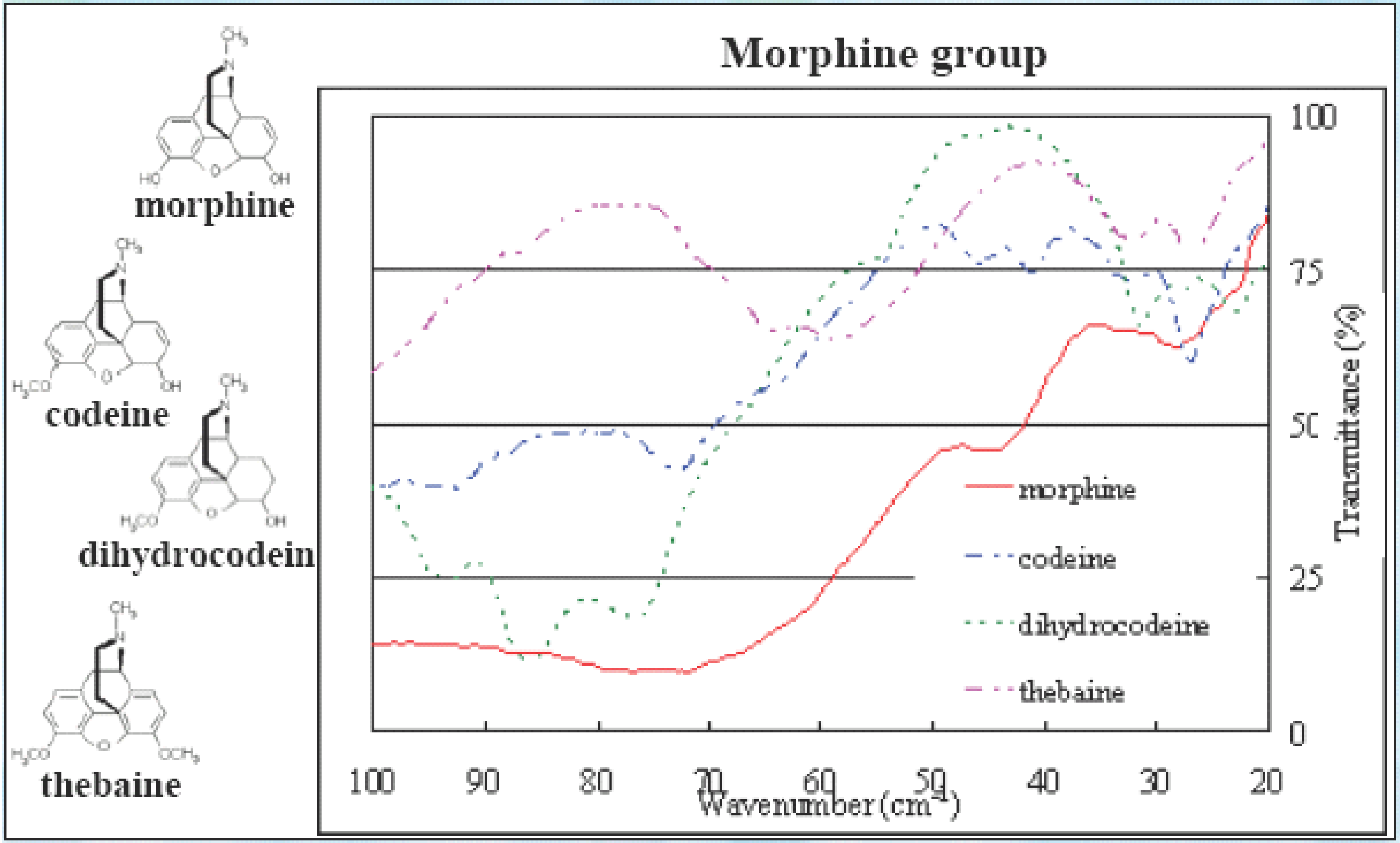
THz beam can penetrates through the plastic cover of IC chips

Defects near the Foam/Substrate Interface of Fuel Tank for Space Shuttle

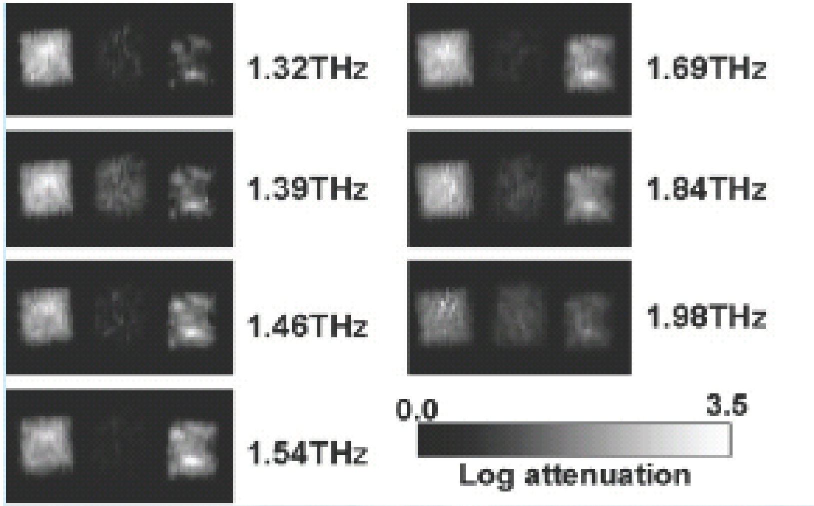


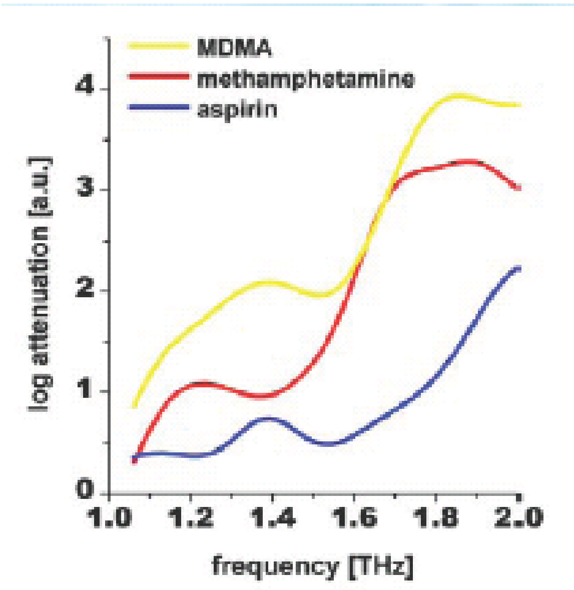
49 of 57 defects were detected

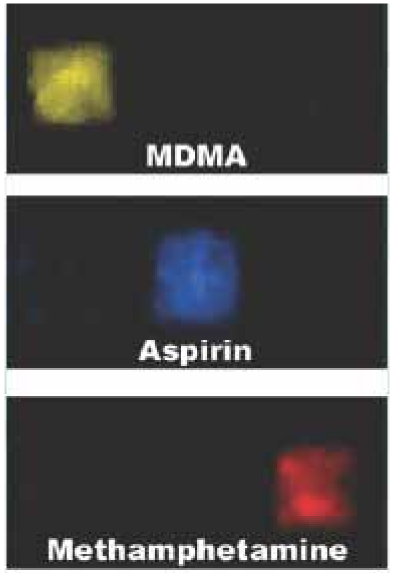
Fingerprint spectra of drugs



Detection of drugs in envelopes



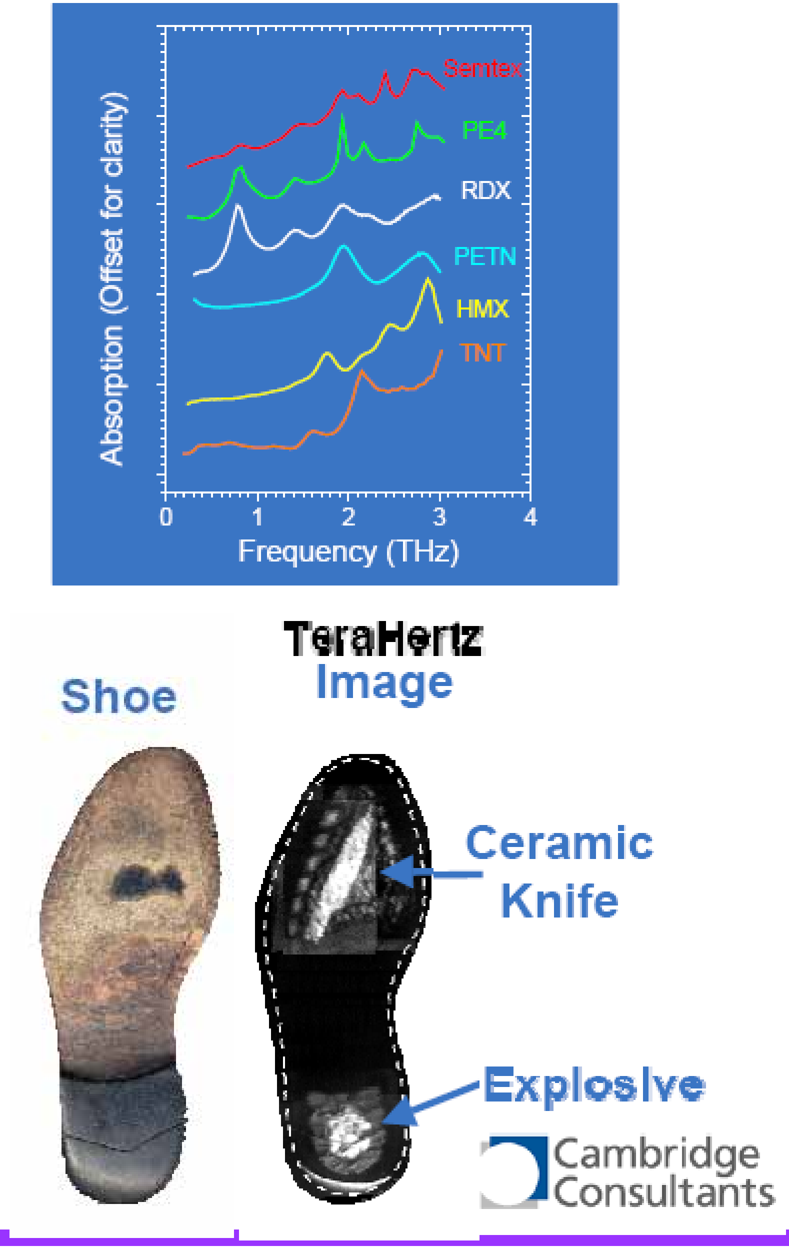




Also works on mixed samples!

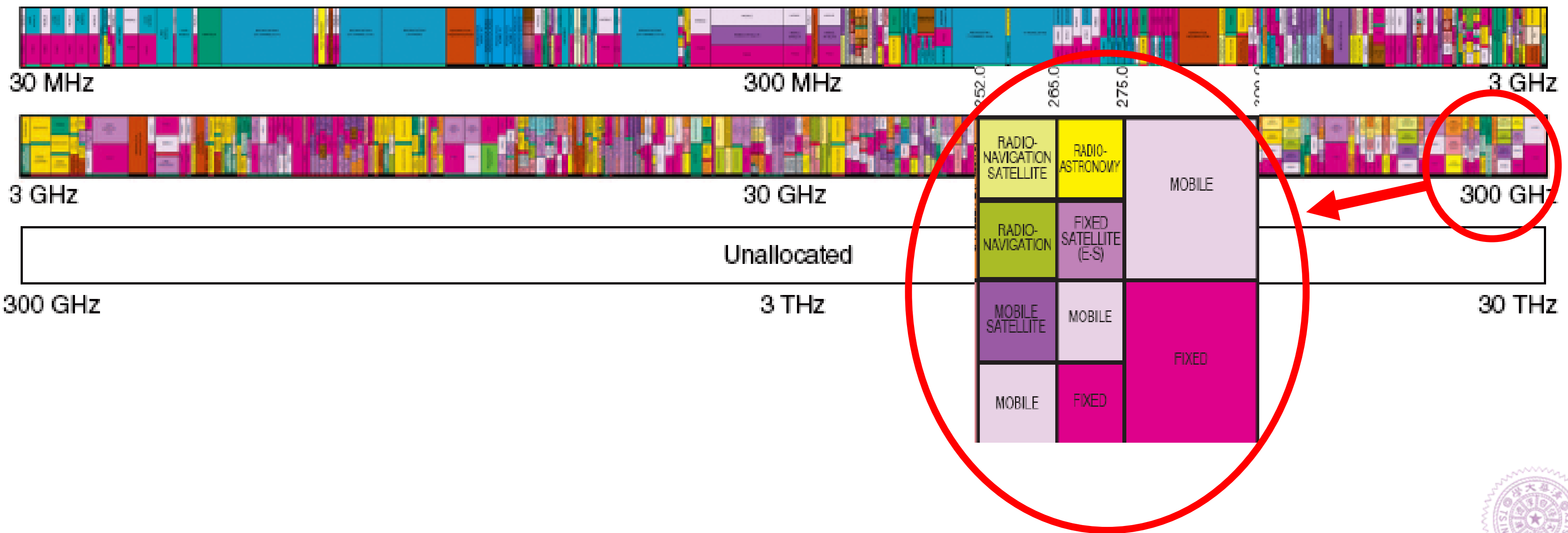
Kawase *et al*, *Opt. Express* **11**,2549 (2003)

THz Technology for Homeland Security

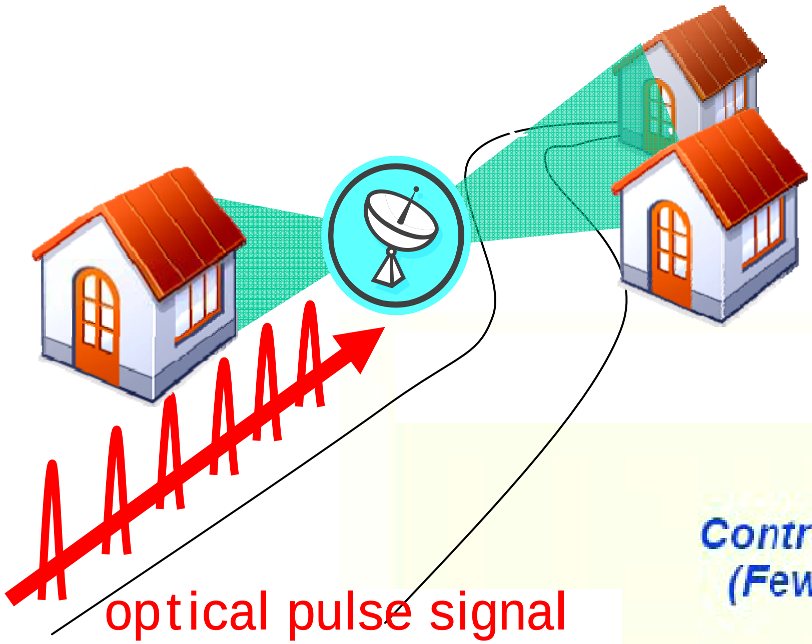


Why Sub-THz or THz wave for Wireless Communication?

- Frequencies above 300GHz are currently unallocated by FCC*
- Very high data transmission rate and secured communication possible (>10Gbits)

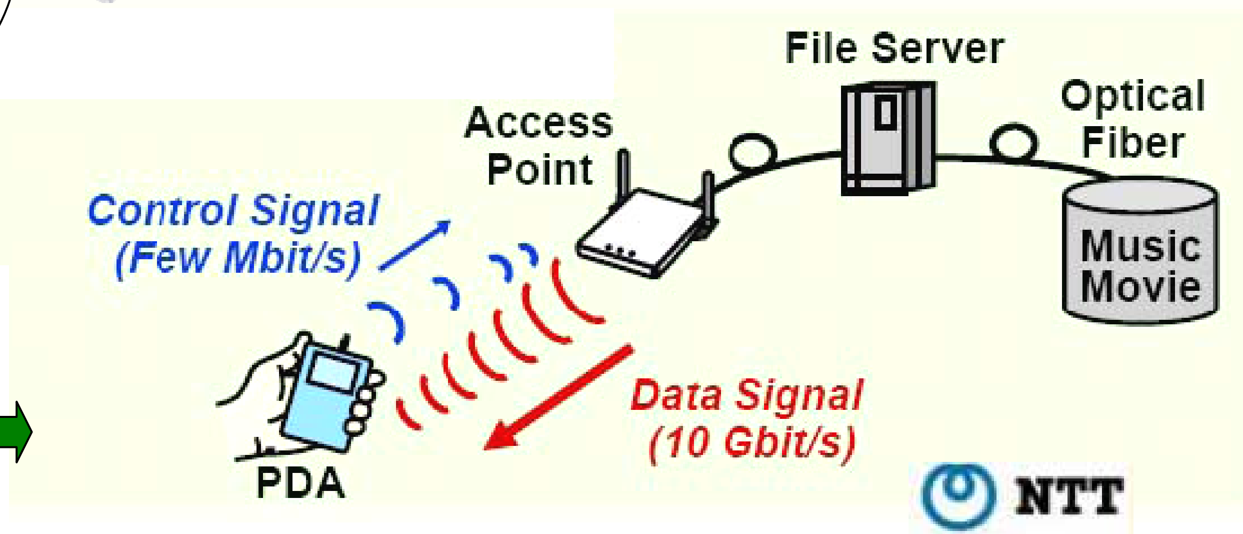


Solving the Last mile problem by The Radio-over-Fiber Scheme



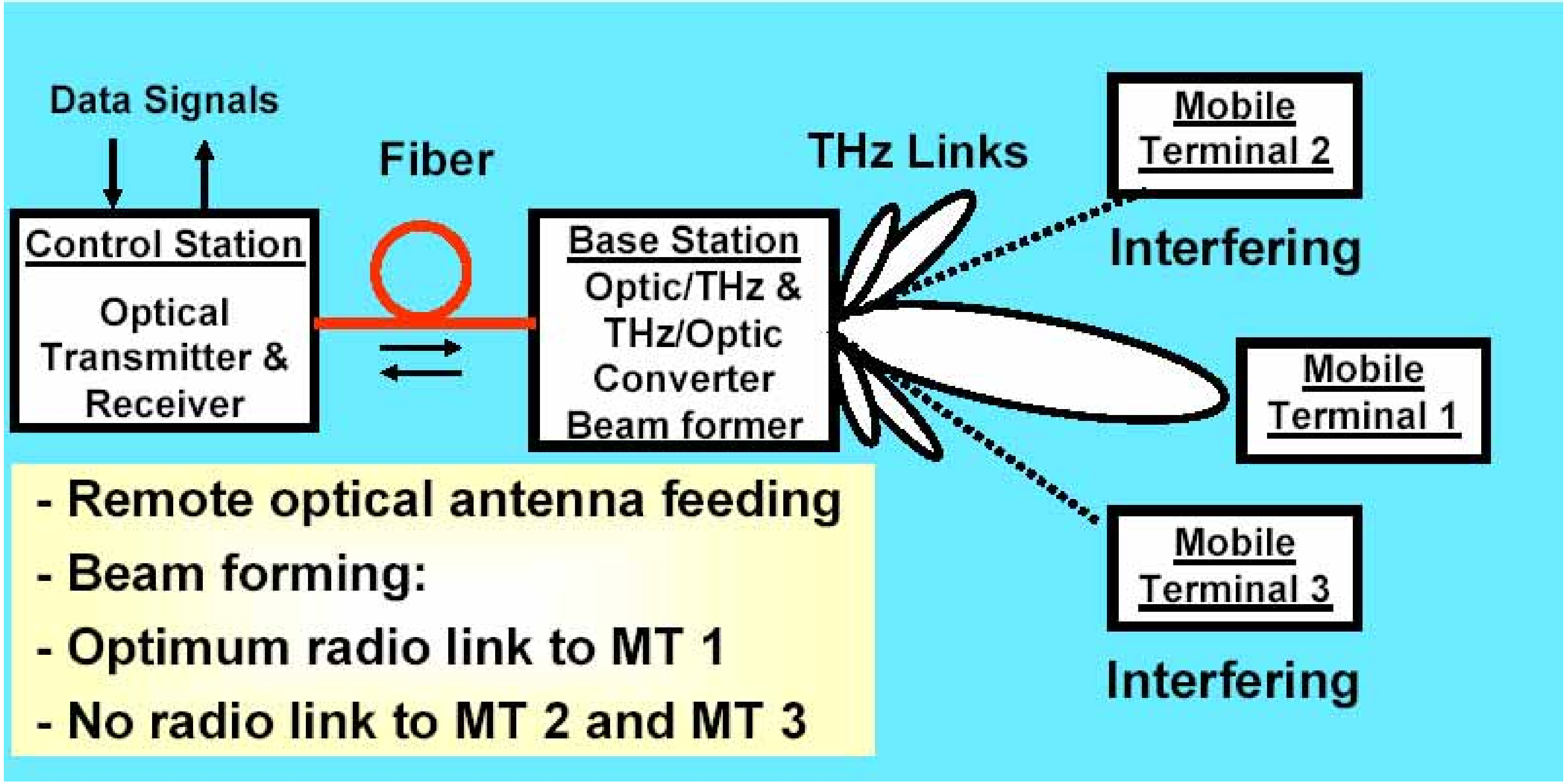
- **The fiber-to-the-home concept is too expensive to make sense for a remote, small village.**

- **A vision from NTT**

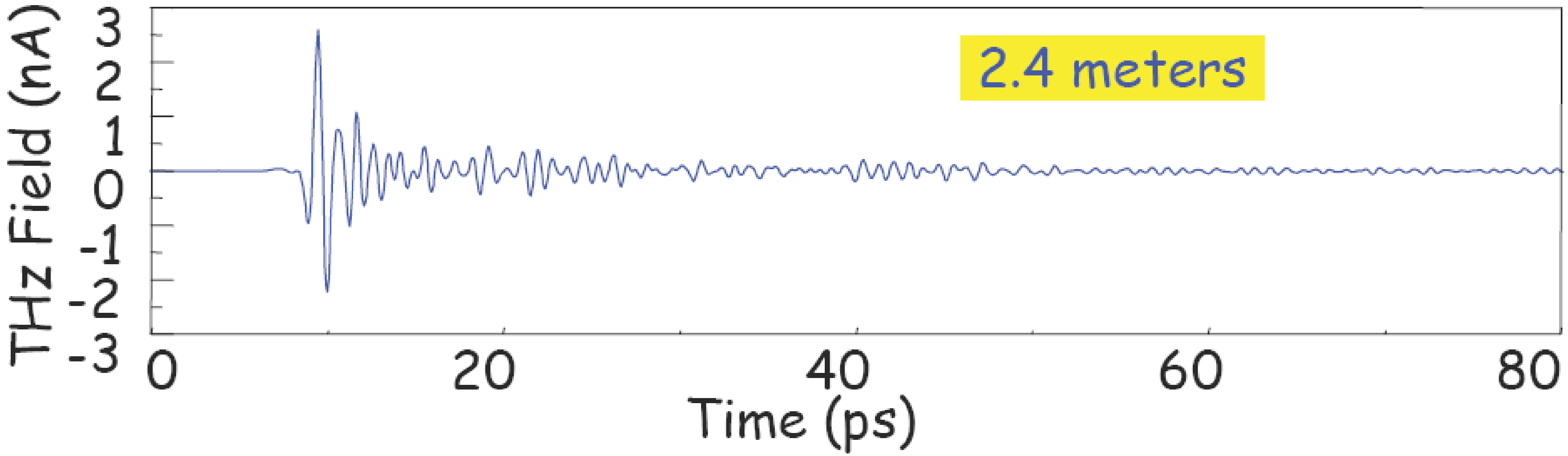


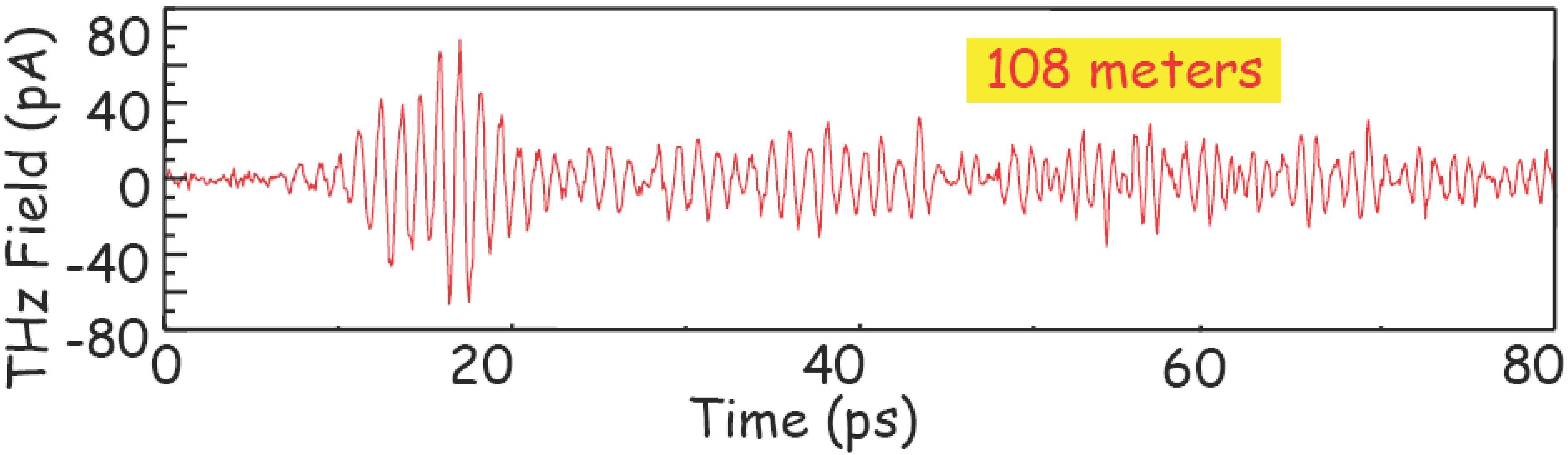
- **<u>The transmission loss and dispersion effect</u> in the long-distance electrical transmission line minimized through the RoF approach.**

Ultra-Wide-Band Fiber-THz Radio Data Communication Link for SNG or Military

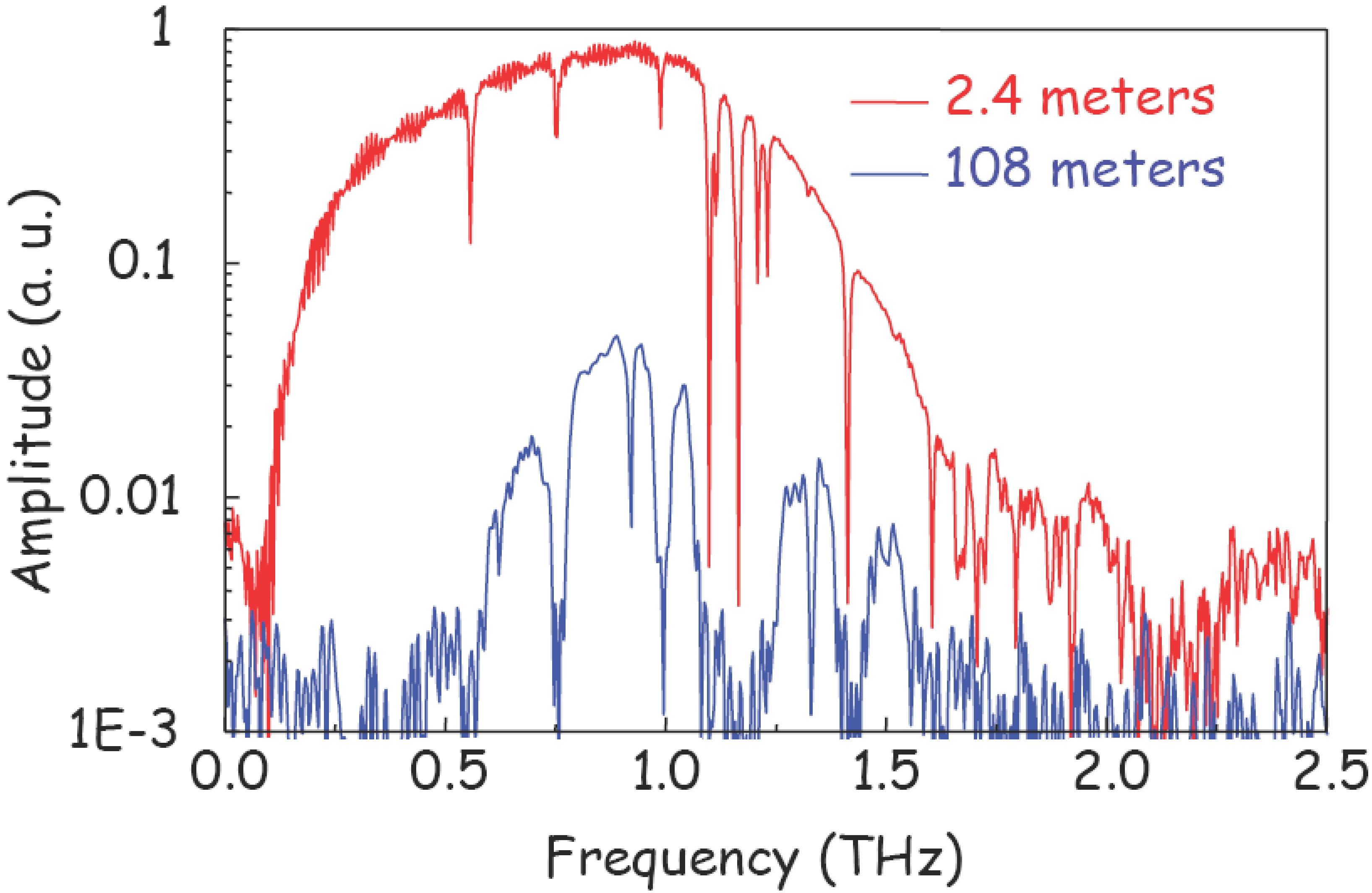


A THz Pulse after 2.4 Meters & 108 Meters



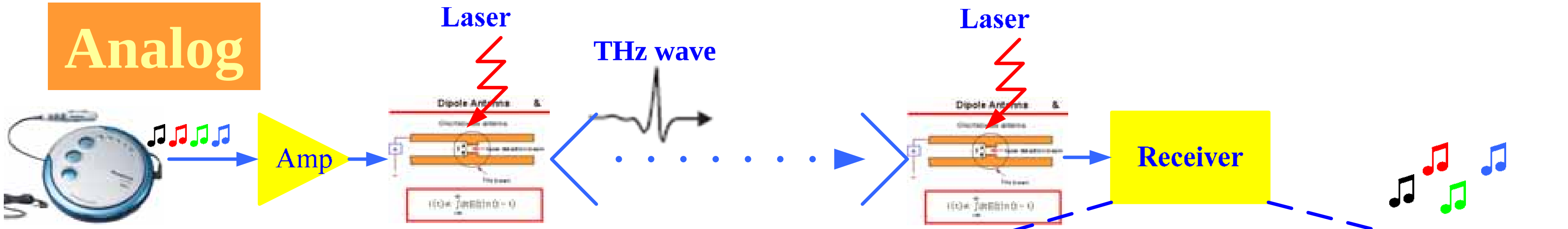


Spectra after 2.4 Meters & 108 Meters

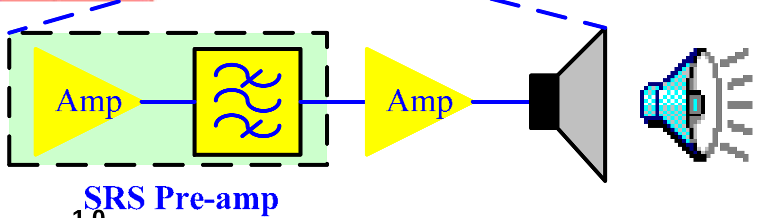


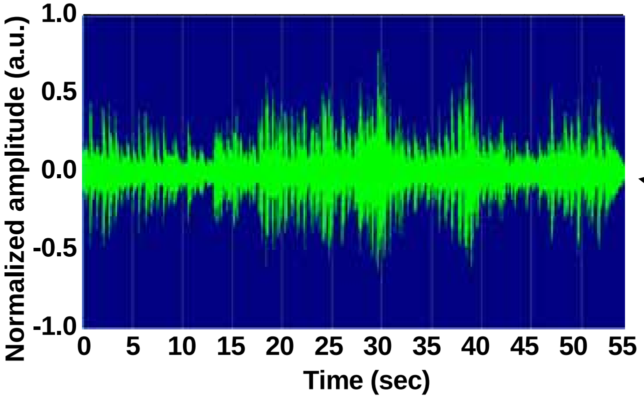
Transmission of burst and audio signal through a Directly-modulated THz communication link

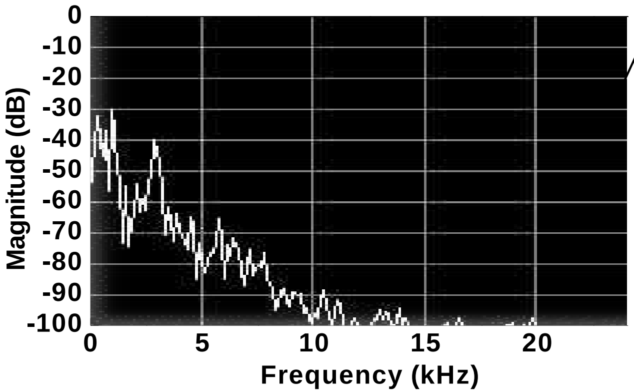
Analog



Opt. Exp.,Dec'05

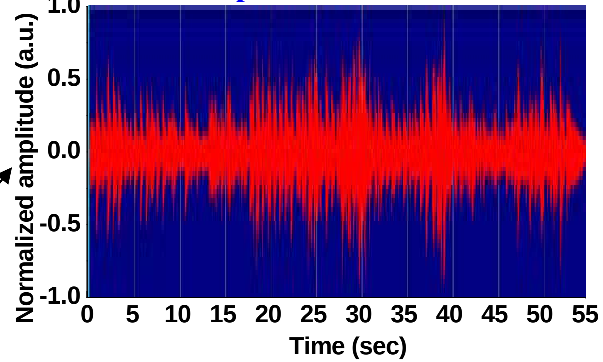


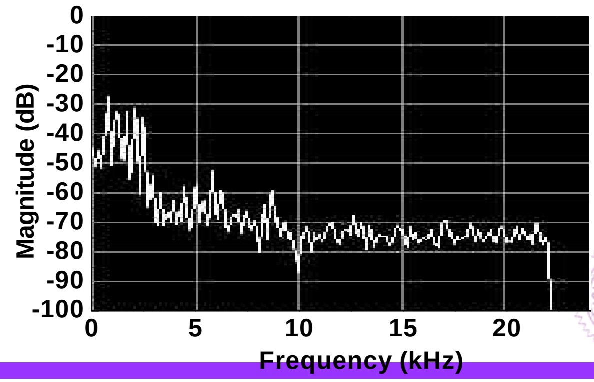




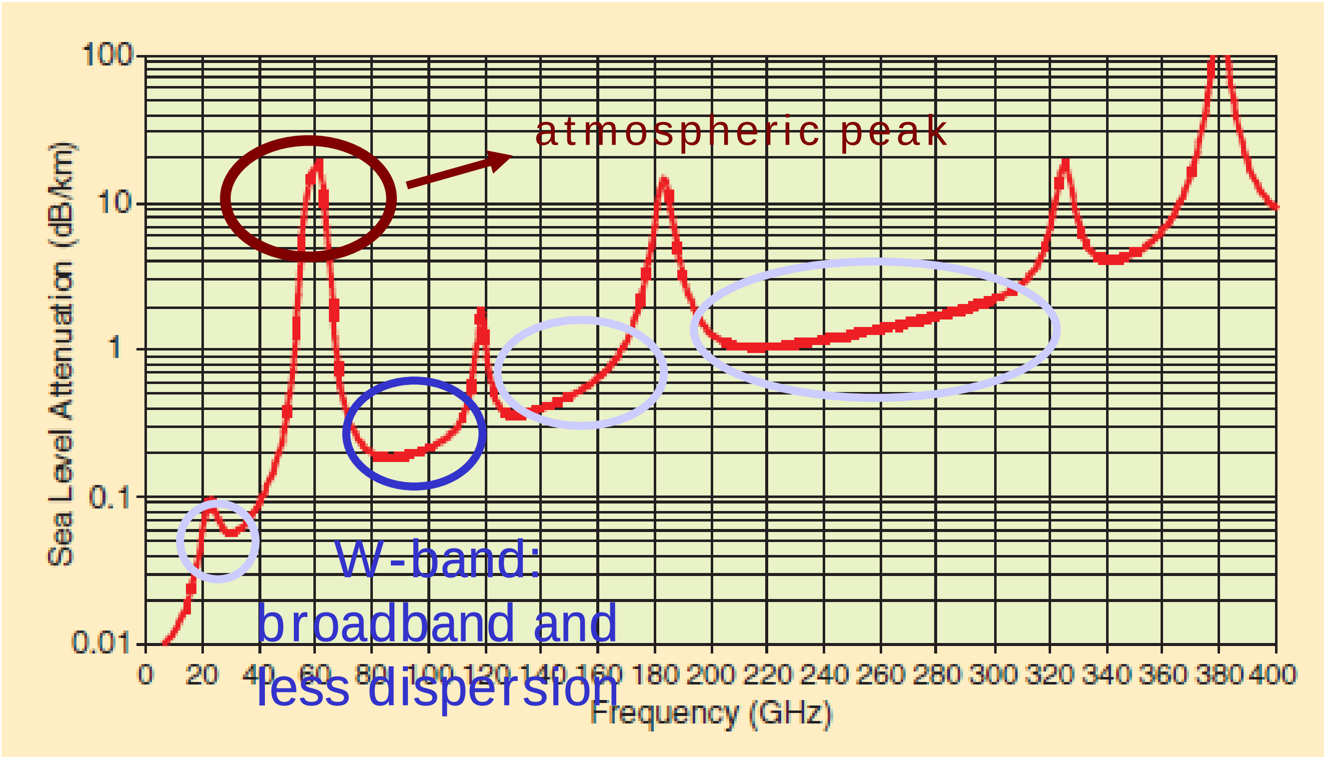
Original music time sequence and a portion of spectrum

Received music time sequence and a portion of spectrum





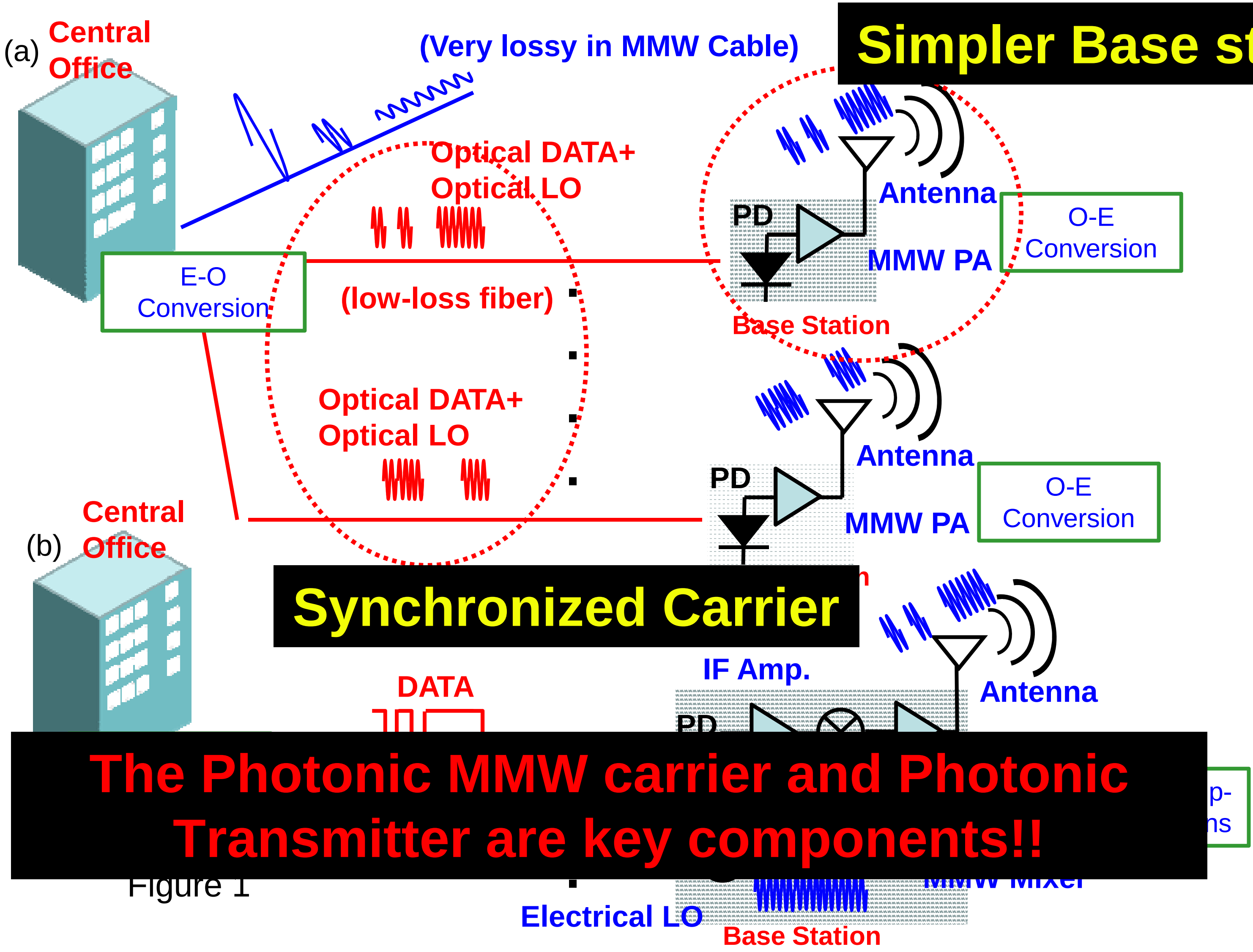
Average millimeter-wave atmospheric absorption



- Transmission distance at 60 GHz is limited due to atmospheric absorption.
- W-band overlaps with an atmospheric window permitting multiple kilometer transmissions.

Jonathan Wells "Fast Than Fiber: The Future of Multi–Gb/s Wireless," *IEEE Microwave Magazine*, pp.104–112, May 2009.

THz Radio over Fiber (RoF) Communication System

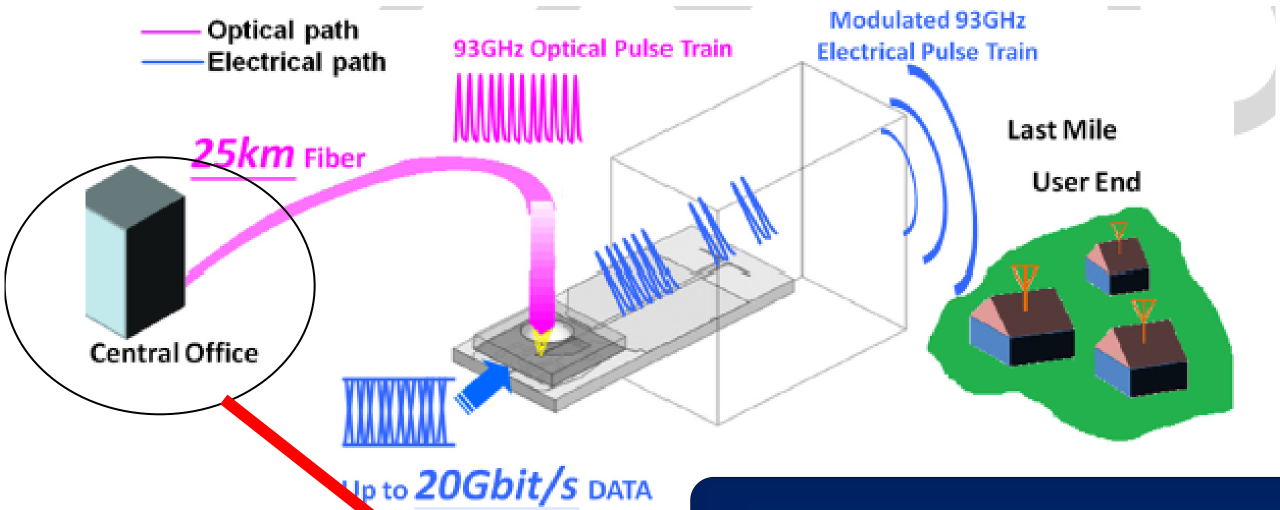


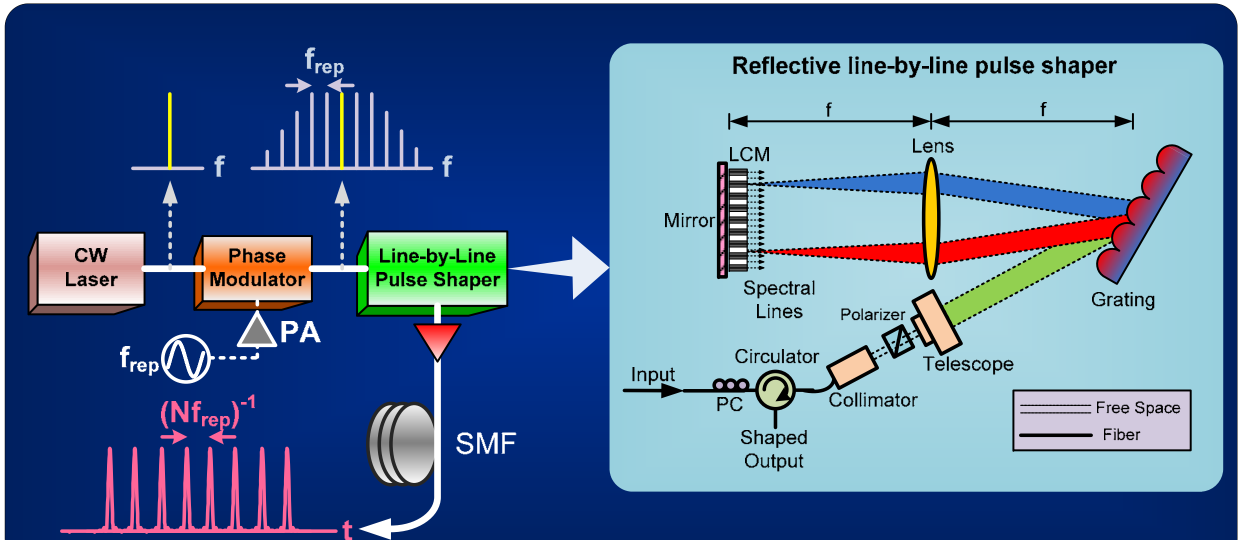
Simpler Base station

Synchronized Carrier

The Photonic MMW carrier and Photonic Transmitter are key components!!

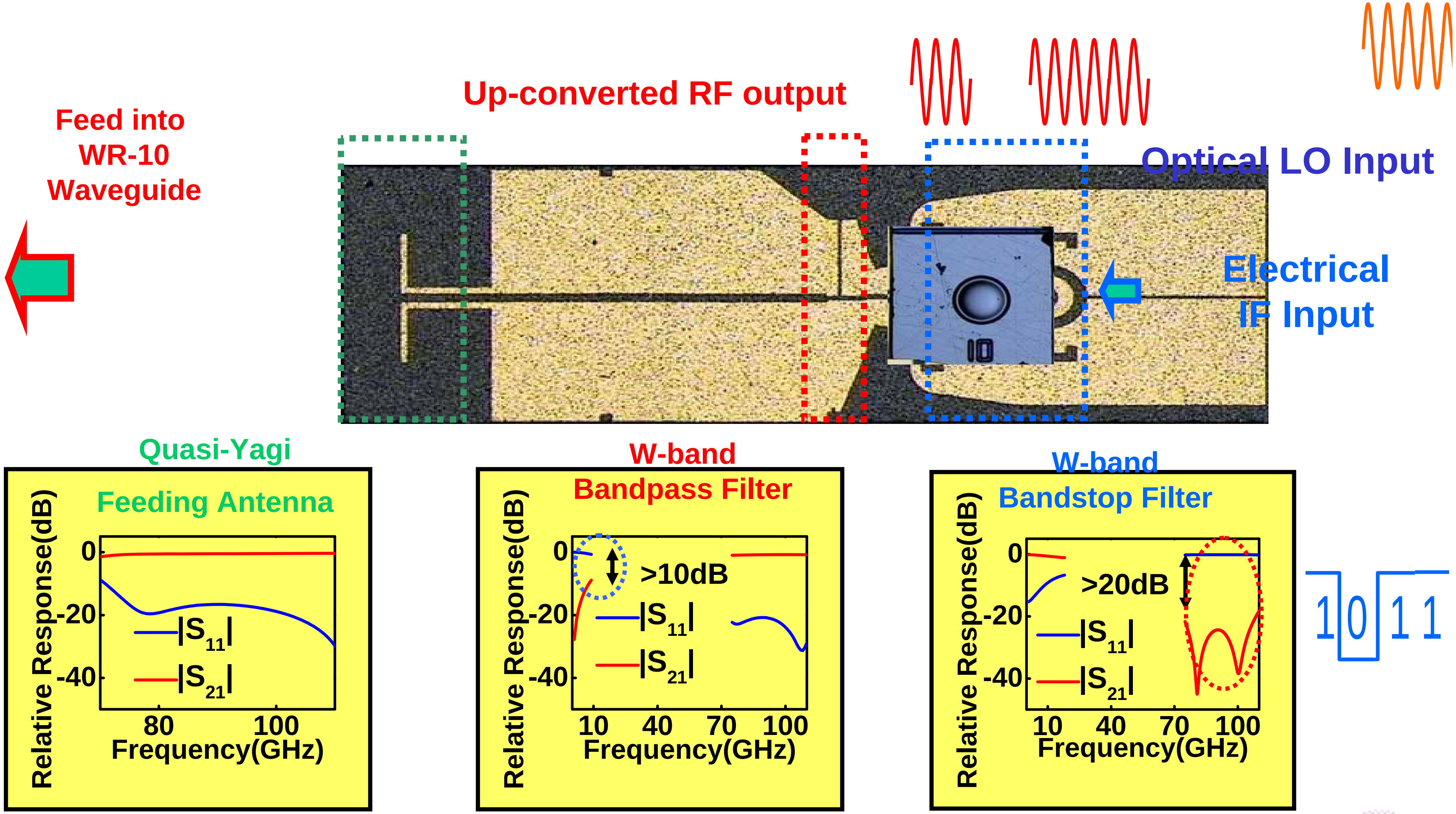
The Photonic Millimeter Wave (MMW) Source



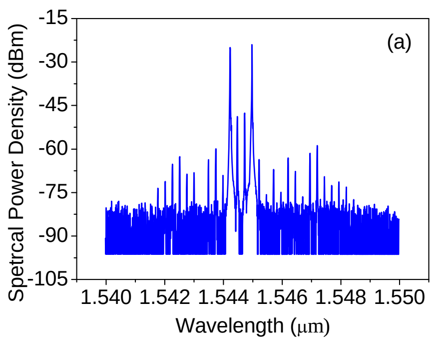


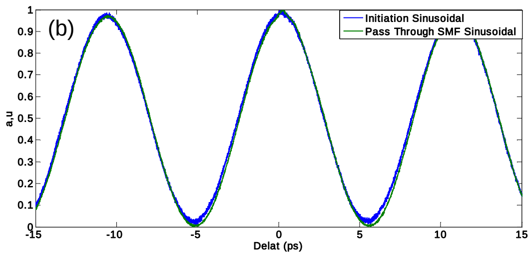
Generate frequency-comb for higher MMW power and >25km delivery!!

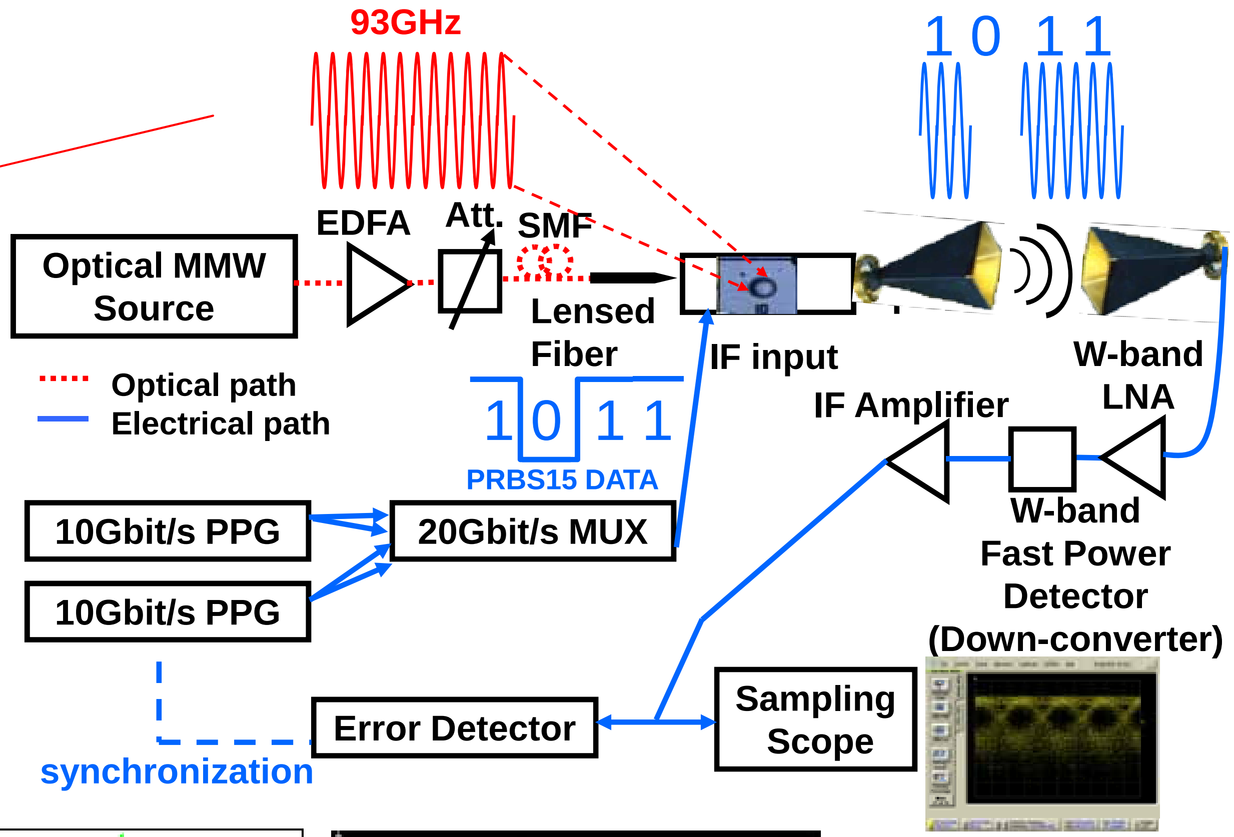
Sub-THz High-Power Photonic Transmitter

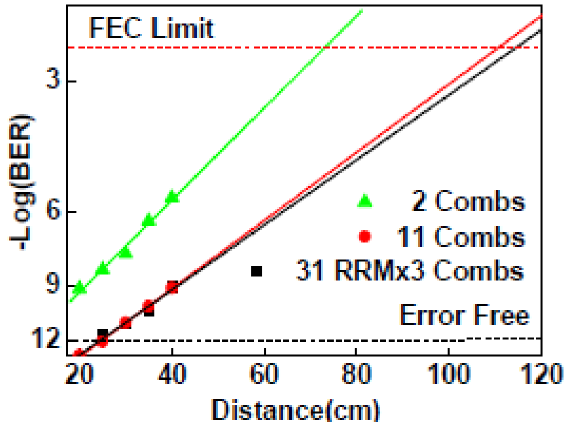


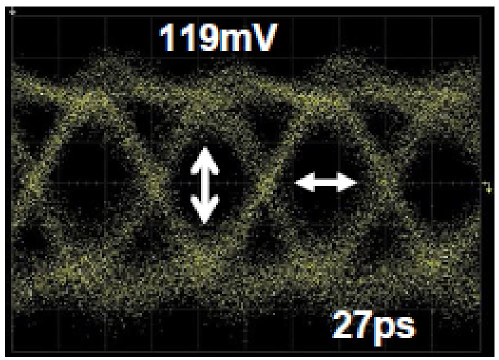
W-band (100 GHz) Data Comm @ 20 Gbit/s





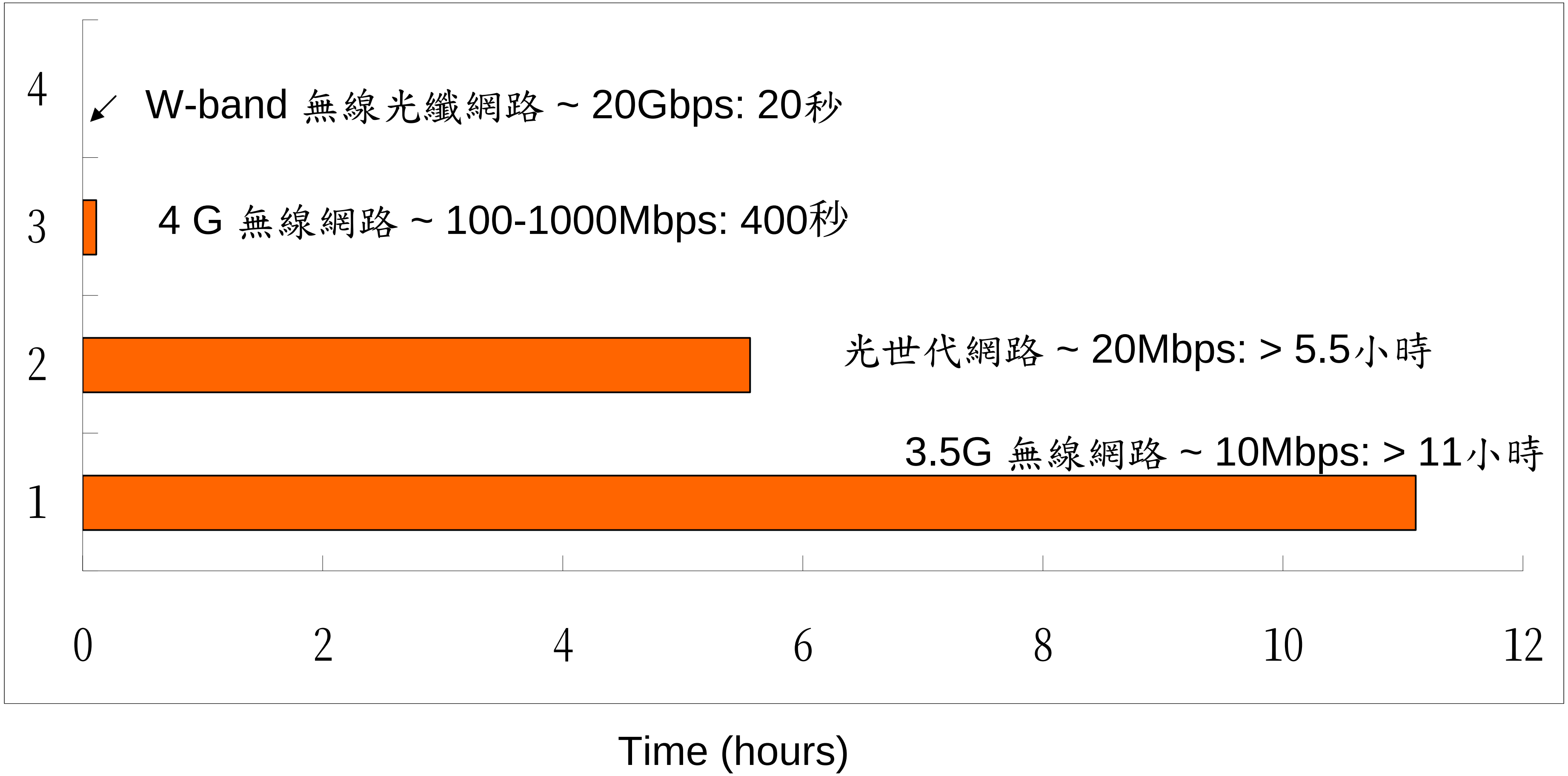




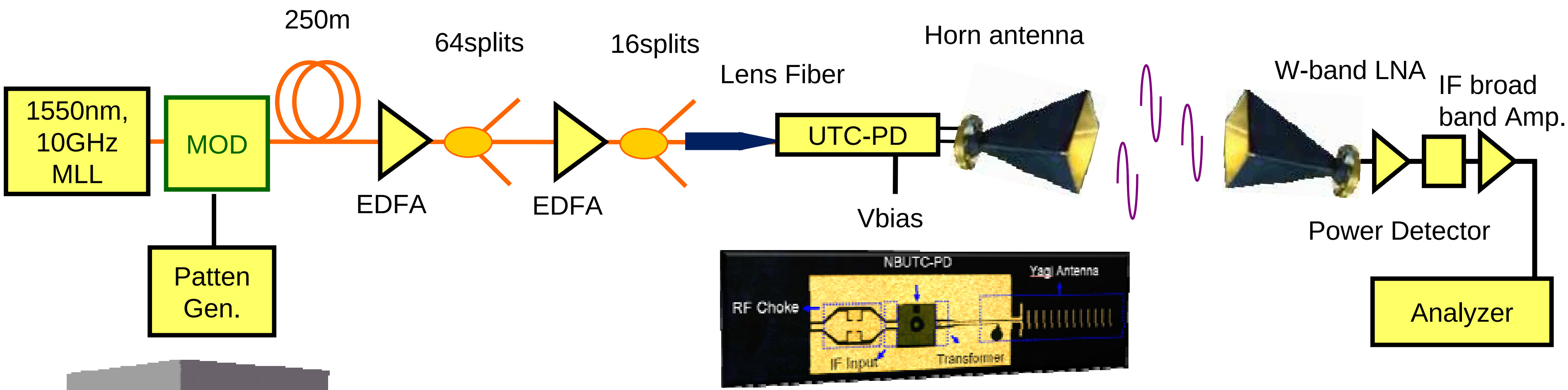


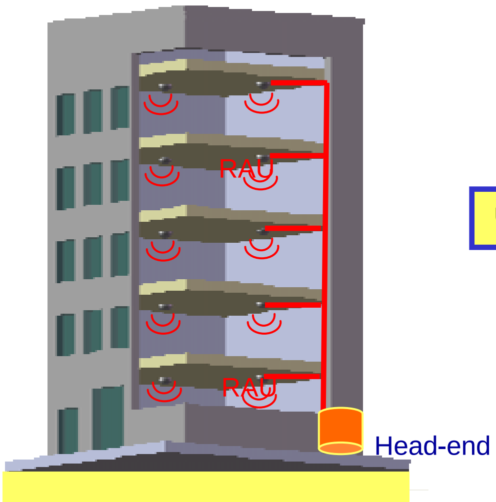
(a)

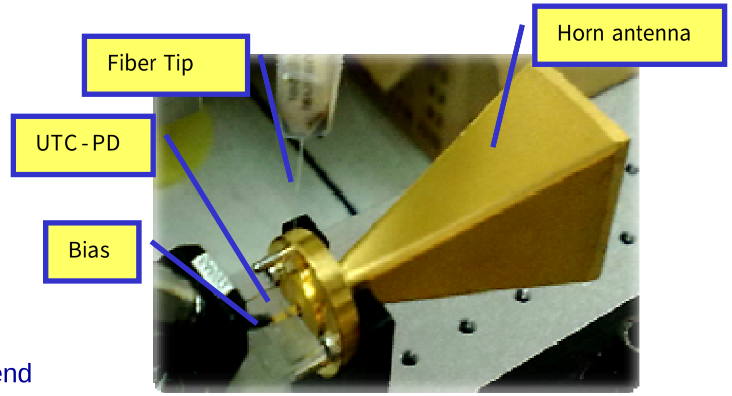
傳送10張 4.7Gbyte DVD碟片:

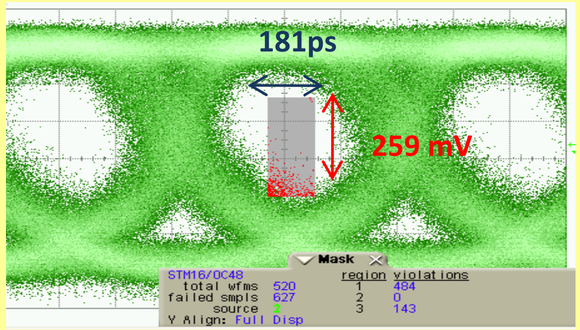


UWB W-band (100GHz) THz Impulse Radio









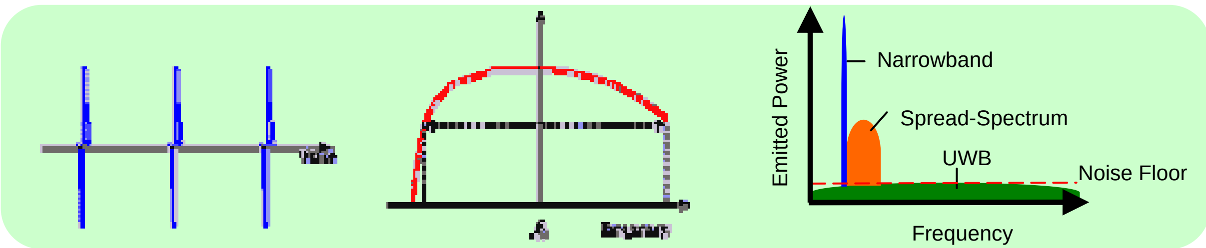
Bias modulation at **2.5Gb/s**

FTTA split-ratio 1024

Input power 45mW

Photo current of device 4.6 mA

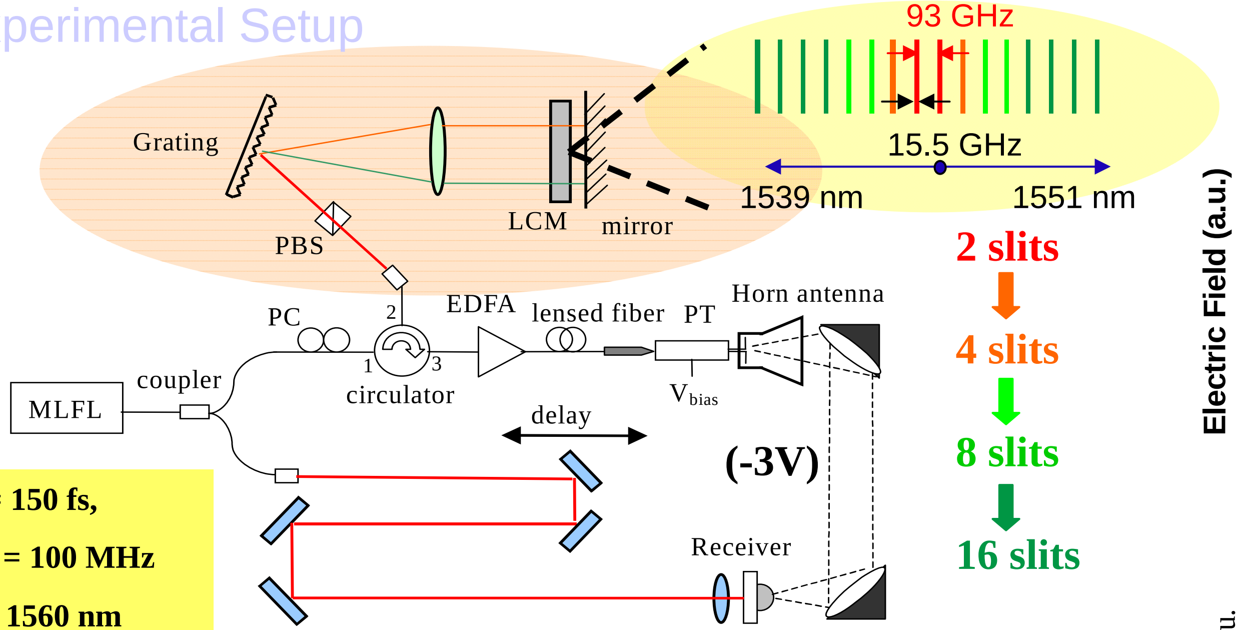
Applied bias 1.9 V ± 0.4V



• *Optics Express* (2010)

Generation of Power-Enhanced
Narrow-Band Sub-THz Signal for Sensing

Experimental Setup

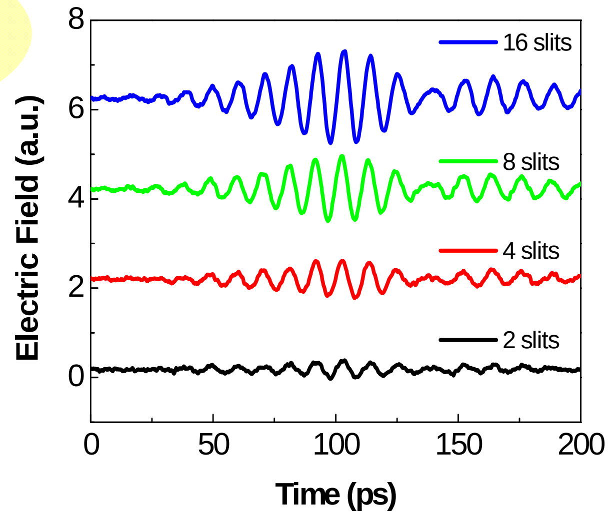


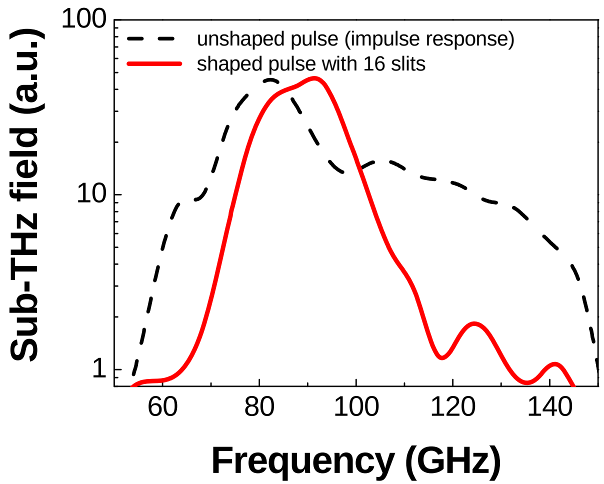
t_p = 150 fs,

f_{rep} = 100 MHz

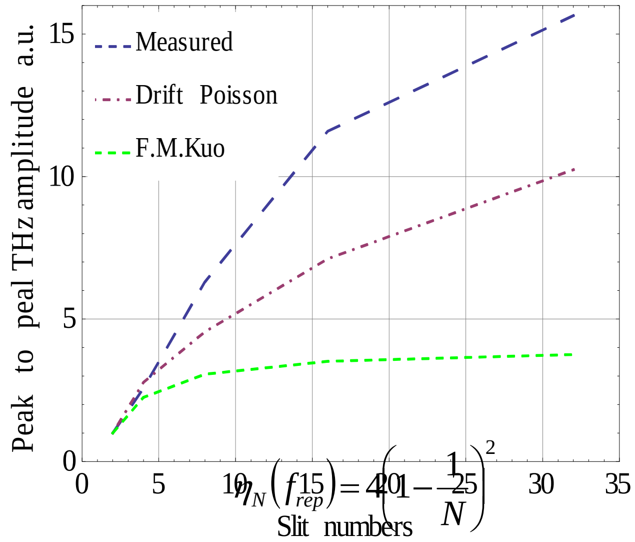
λ = 1560 nm

Measured MMW waveforms



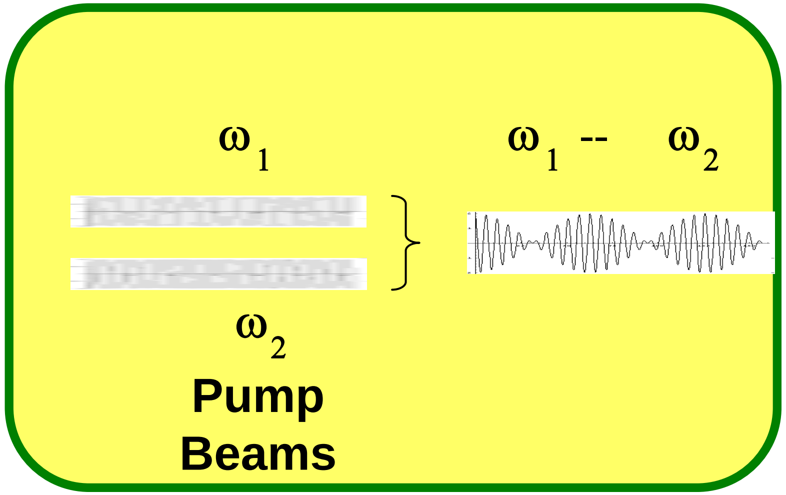


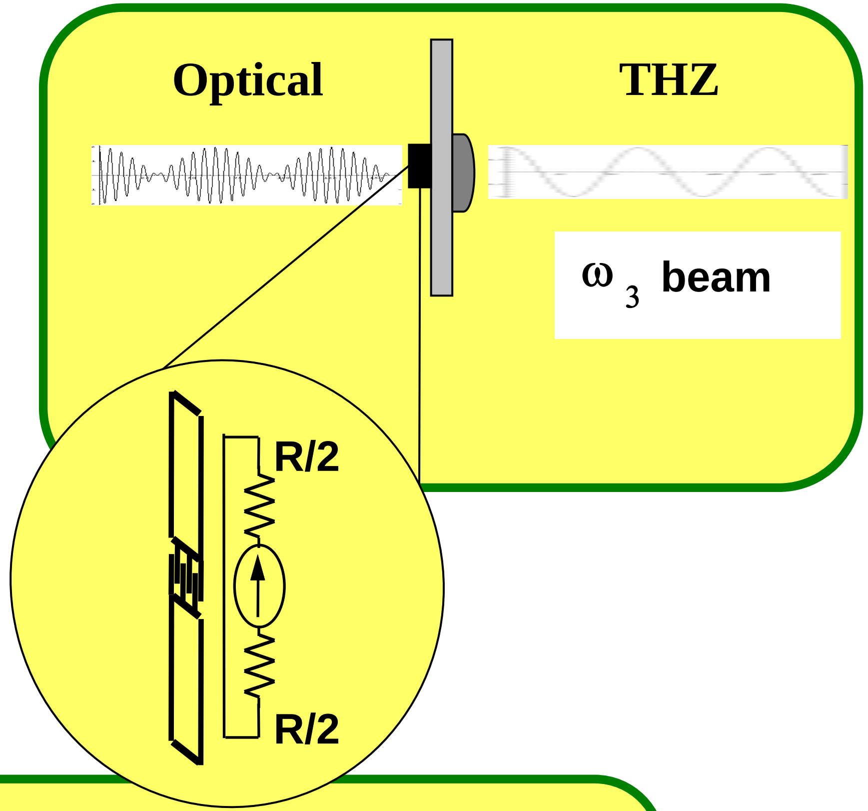
- Tunable (60-142 GHz)
- Enhancement ≥25 ×, peak power > 500 mW
- Low bias (~ 3V) and exiting power (< 5mW)



$$\eta_N(f_{rep}) = 4\left(1 - \frac{1}{N}\right)^2$$

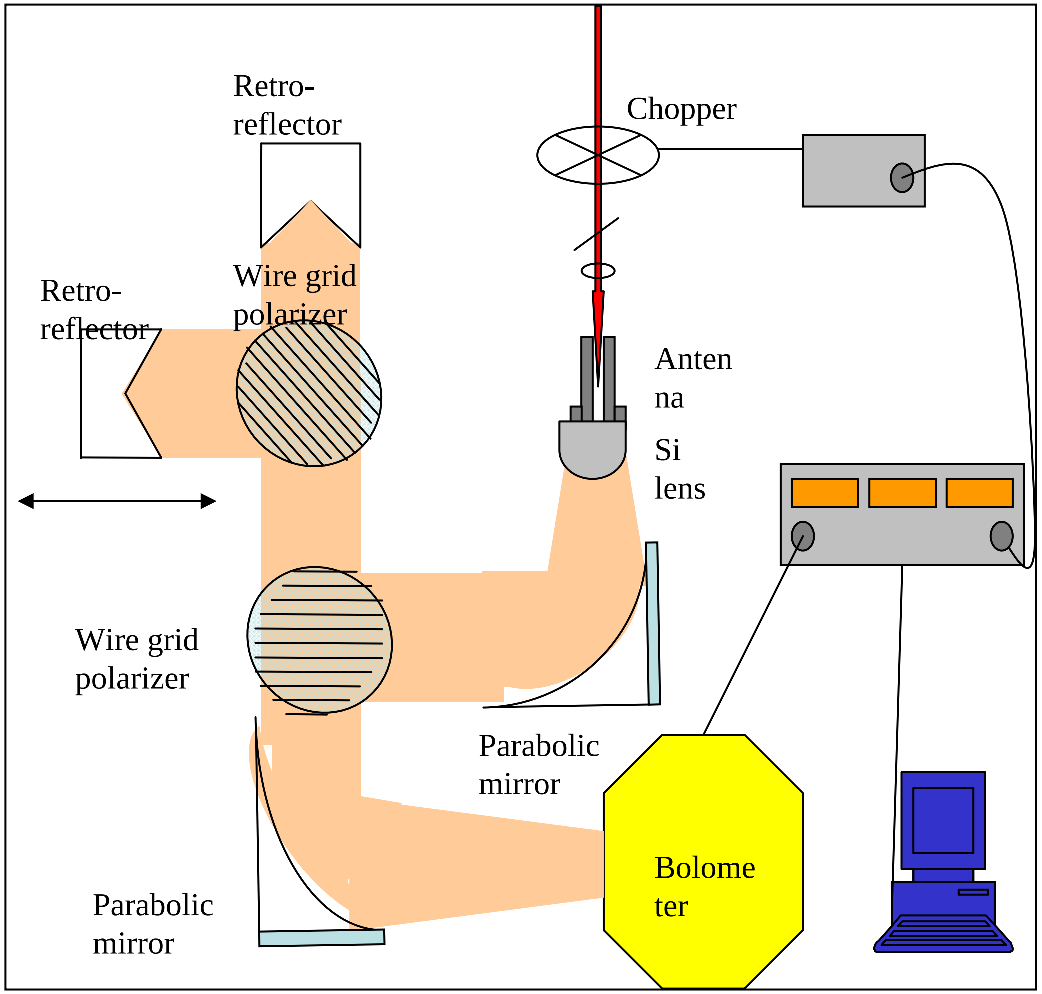
CW THz Generation by Photomixing or Heterodying

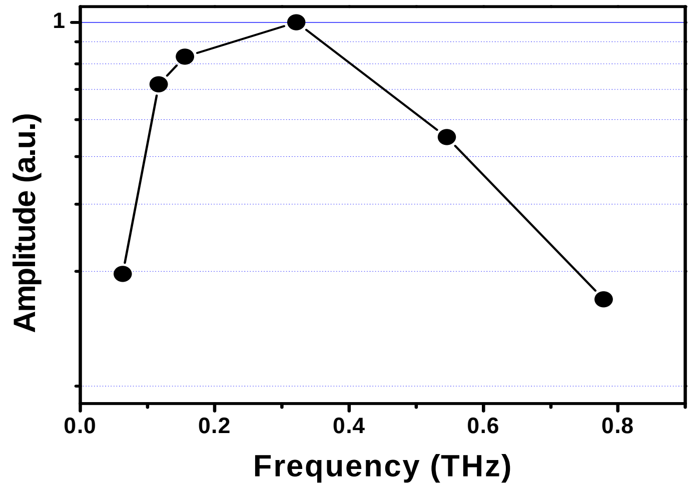


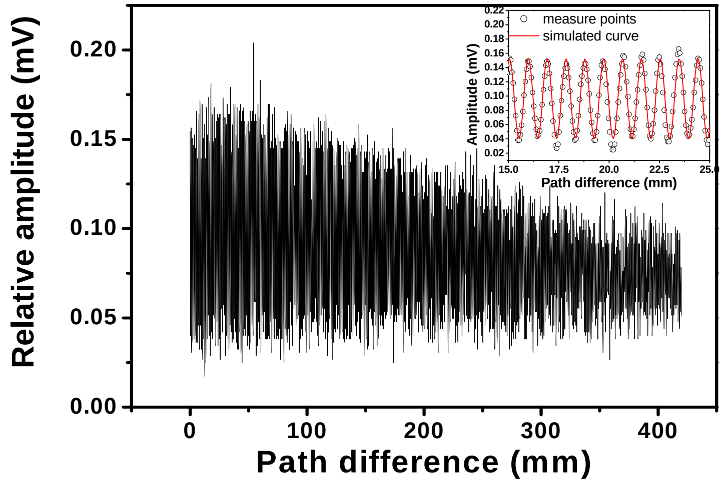


$$P_3 = \frac{R}{2}\eta_1\lambda_1\eta_2\lambda_2\left(\frac{eg}{hc}\right)^2 \frac{P_1 P_2}{\left[1+(\omega_3\tau)^2\right]\left[1+(\omega_3 RC)^2\right]}$$

CW THz Generation w/ 2 LDs

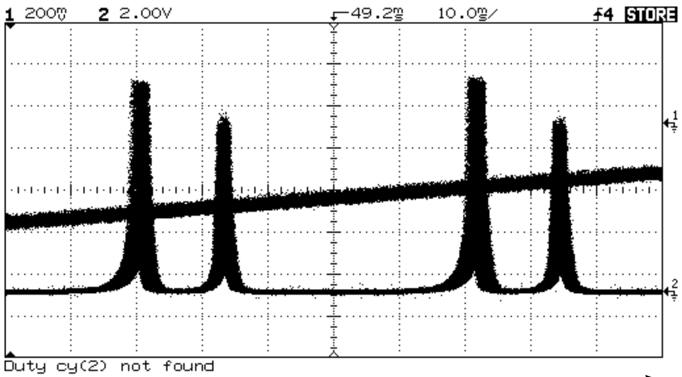


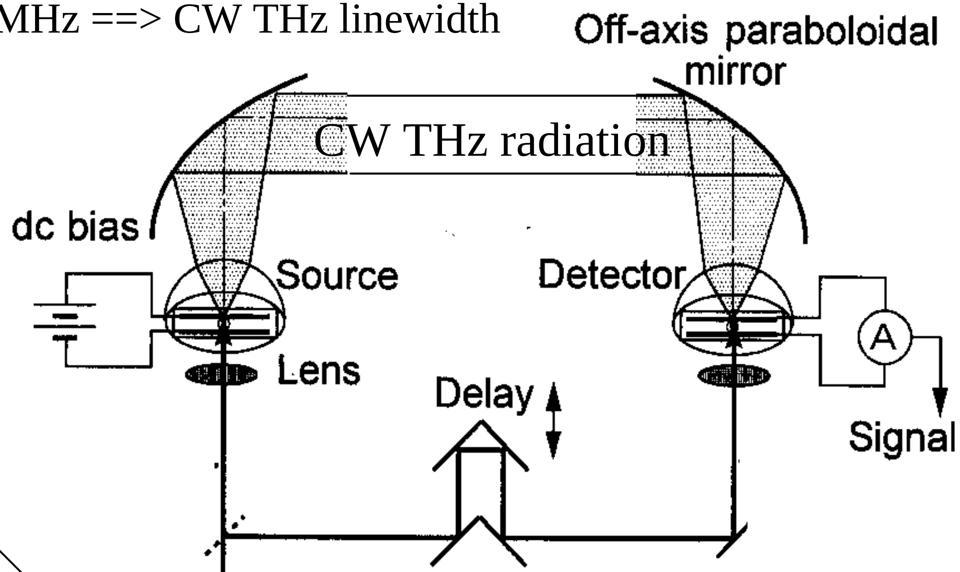


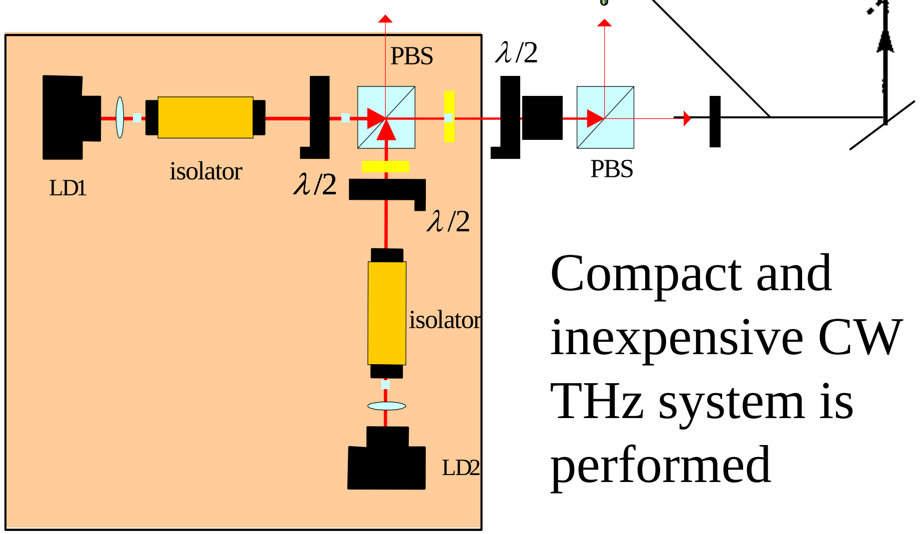


Narrow line width CW THz radiation generation and detection by photoconductive antenna

Dual wavelength frequency stability~250MHz ==> CW THz linewidth







Compact and inexpensive CW THz system is performed