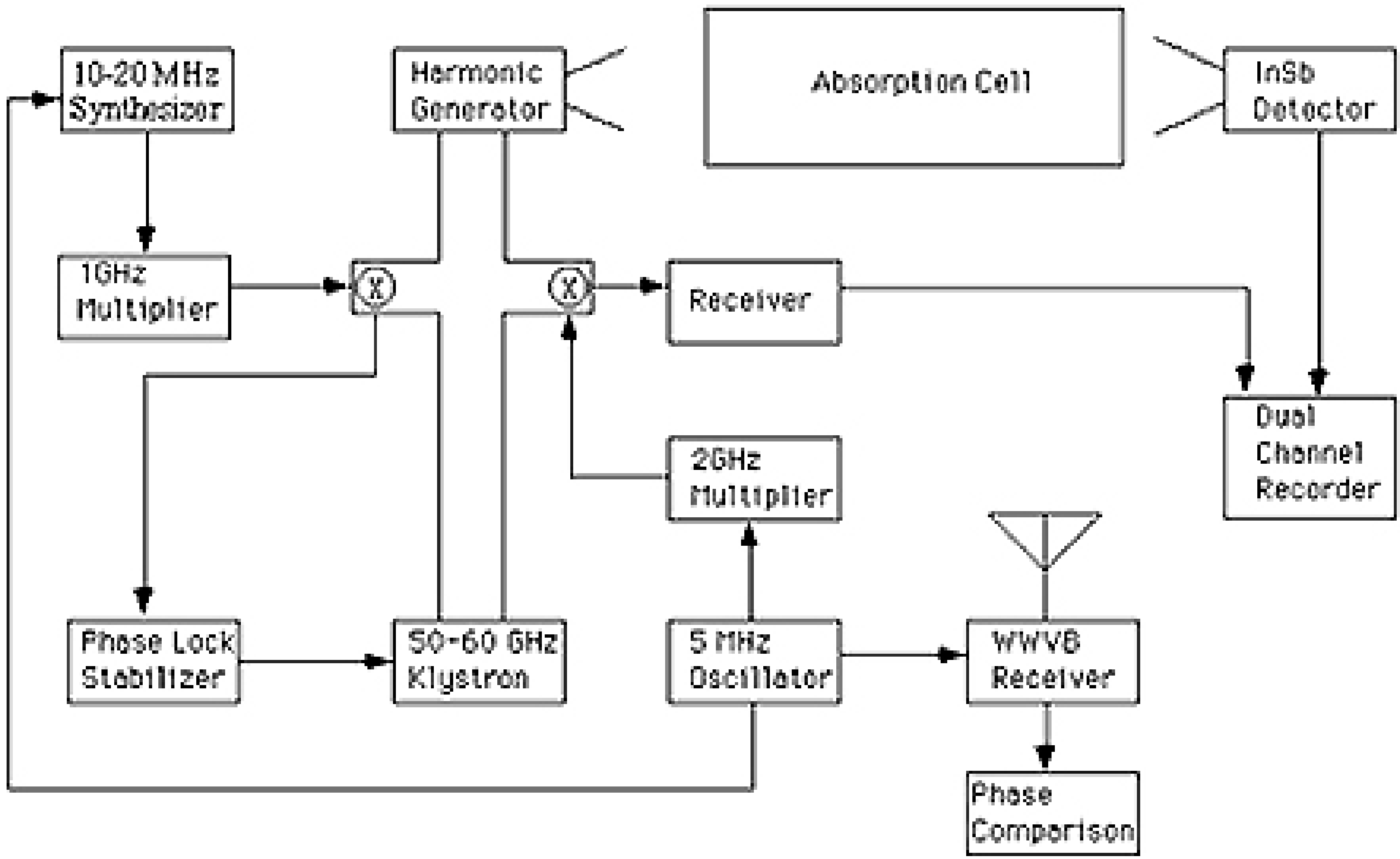
THz Science, Technology, and Systems

- The best motivation for students and researchers entering a new field is often the scientific history and systems applications.
- This first set of notes provides some highlights from three scientific and application areas: (1) spectroscopy, (2) radio astronomy, and (3) concealed-object imaging, and (4) biomedical imaging.
- We will also contrast the investment perspectives from the Government and from Private Industry. Both sectors are actively involved in the THz field, more so than any other time in history.
- Will also summarize some of the “grand challenges” that THz researchers and engineers are presently facing – challenges that certainly qualify as good Ph.D. Thesis topics !

THz Spectroscopy

- Historically was the first application in THz region and based on the rotational transitions of many vapor-phase molecules that occur in this region.
- **1950s**: THz spectroscopy of gas-phase molecules started using frequency multiplication of microwave and mm-wave vacuum-tubes (W. Gordy et al). Continual growth of frequency multiplier technology since that time.
- **1960s**: THz spectroscopy of solids and liquids started in the 1960s with the advent of a simple instrument – the Fourier transform spectrometer. Much pioneering work done on the dielectric properties of plastics, semiconductors, and ceramics (H. Gebbie, P. Richards, K. Button, et al.)
- **1970s**: High-resolution (i.e., "line") astronomy with advent of ultrasensitive cryogenic heterodyne receivers above 100 GHz the discovery of CO rotational ladder and other small molecules in nebular regions (T.G. Phillips et al.)
- **1970s:** Low-resolution astronomy with the advent of ultrasensitive cryogenic (composite) bolometers and the discovery of the cosmic background blackbody peak (P. Richards et al).
- **1990s:** Spectrometric imaging becomes possible with the advent of ultrafast photoconductive techniques: time-domain and photomixer spectrometry

An Early High-Resolution THz Spectrometer



(from Website of Prof. F. DeLucia; http://www.physics.ohio-state.edu/~uwave/energyspec.html)

Spectroscopic Figures-of-Merit

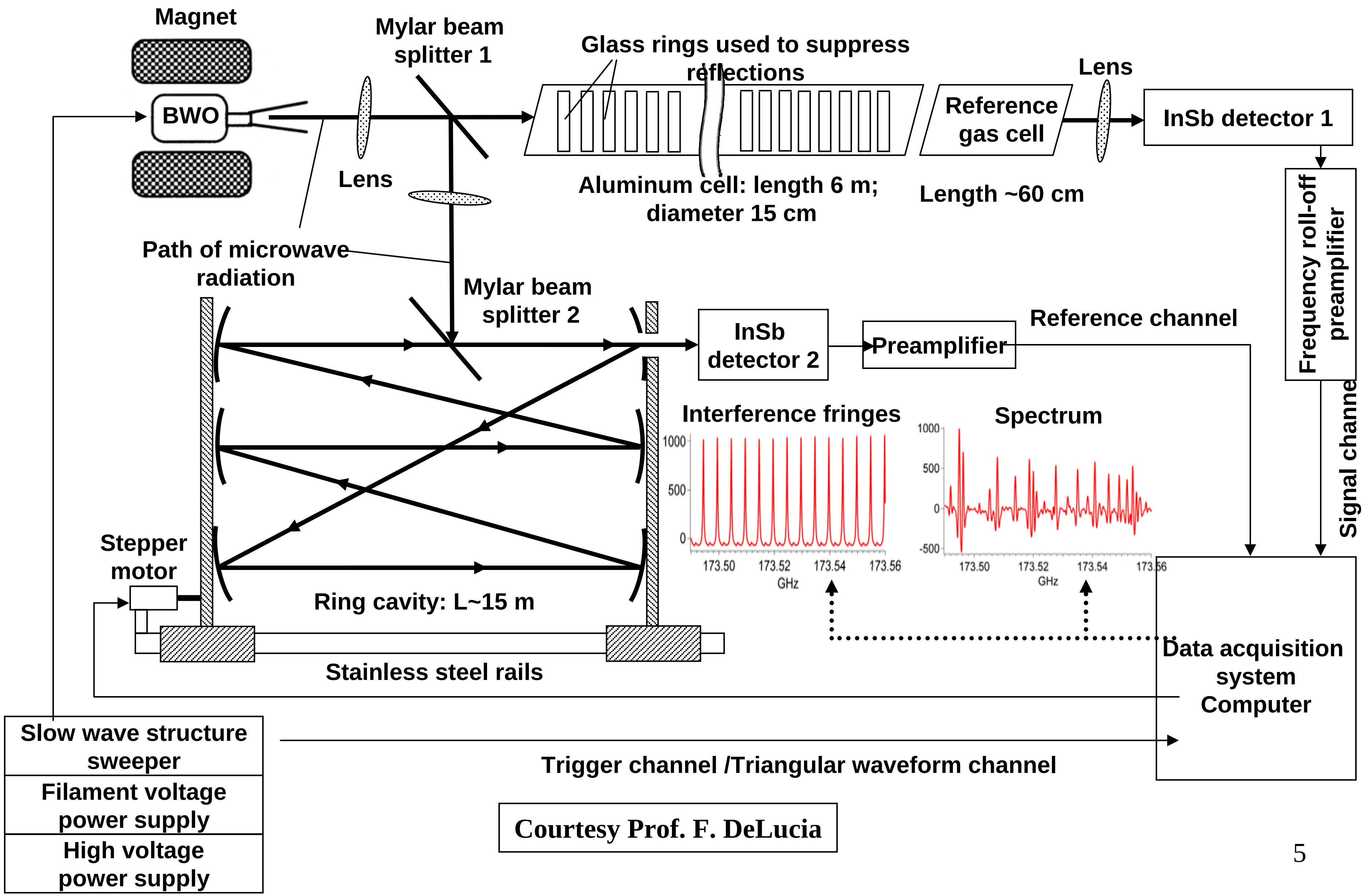
- Resolution, $\delta\nu$ (instantaneous linewidth)
  - Low resolution $\delta\nu > 0.1\ cm^{-1}$ (3 GHz or higher);
    Fourier Transform and Time-Domain
  - Moderate resolution $0.0001\ cm^{-1}$ (3 MHz) $< \delta\nu < 0.1\ cm^{-1}$ (3 GHz)
    photomixer spectroscopy, FASSST (vacuum-tube)
  - High resolution $\delta\nu < 3$ MHz
    frequency multiplier-based spectroscopy

- Frequency tuning $\Delta\nu = \nu_{max} - \nu_{min}$
  - Broadband incoherent (frequency multiplexed), $\Delta\nu >> 1$ THz
    Fourier transform and time-domain
  - Broadly tunable coherent $\Delta\nu > 1$ THz (photomixing)
  - Moderatlly tunable coherent - $\Delta\nu > 100$ GHz (BWOs)
  - Slightly tunable coherent $\Delta\nu < 100$ GHz (Frequency multiplier chains)

- Average power P_{ave} (at ~ 1 THz)
  - "High": $P_{ave} > 1$ mW (BWOs)
  - "Moderate" $0.1 < P_{ave} < 1$ mW (Frequency multiplier chains)
  - "Low" : $P_{ave} < 0.1$ mW (time domain switches, photomixers)

FASSST Spectrometer

Department of Physics
Microwave Laboratory



Courtesy Prof. F. DeLucia

BWO-Based FASSST Spectrometer

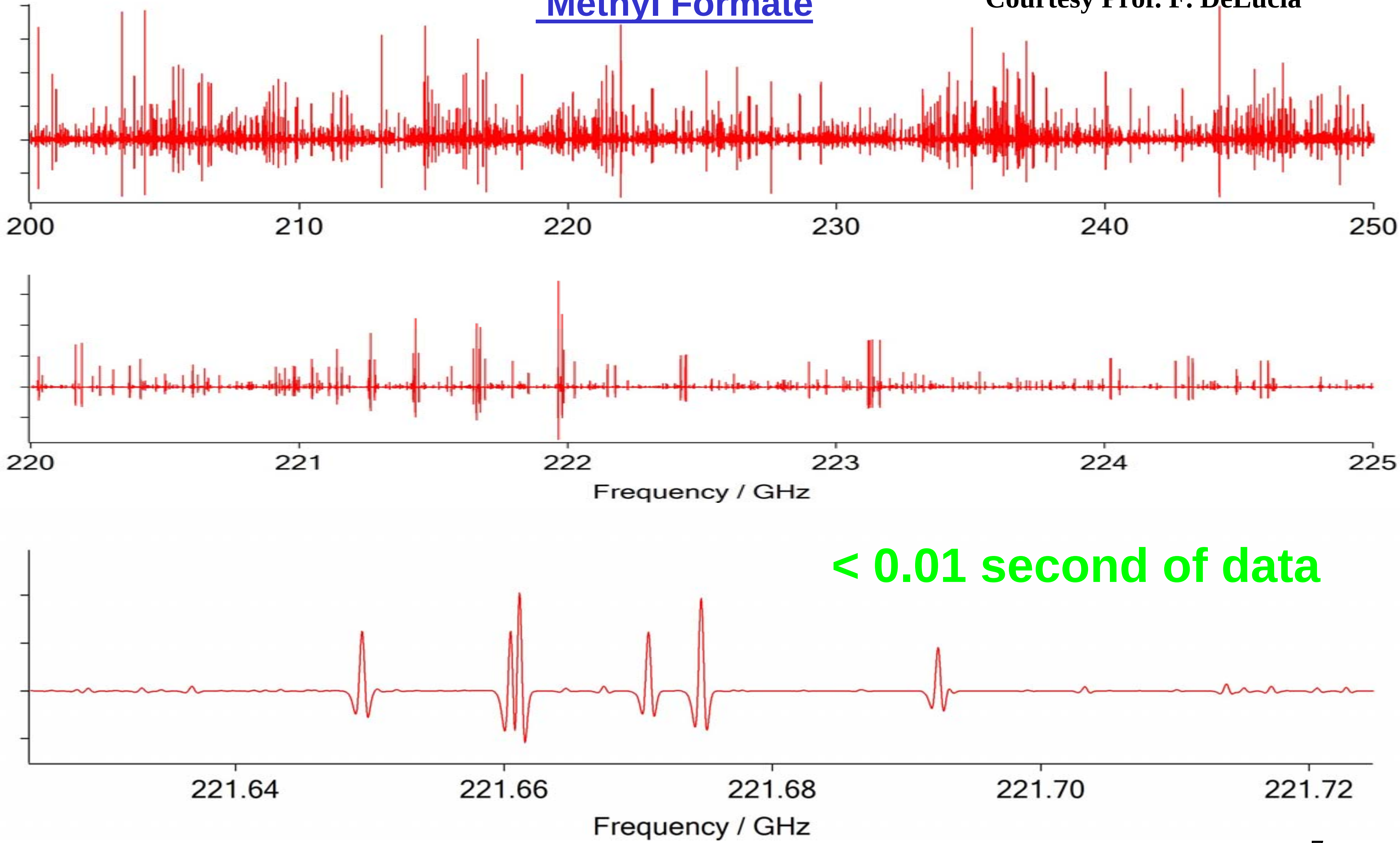
The FAst Scan Submillimeter Spectroscopic Technique (FASSST) spectrometer takes advantage of the high spectral purity of the backward wave oscillator (BWO) and uses a fast sweep (~ 10^5 linewidths/sec) to "freeze" instabilites associated with power supply ripples, thermal drift, etc. Because ~ 10^6 points are recorded (in 1 - 10 seconds), it is not possible to display a spectrum in its entirety here. However, the sequence of successive blow-ups illustrates the results. Because of the fast sweep, ~ 10^6 Hz of detection bandwidth was used to record the spectrum. The use of a bandwidth typical of high resolution microwave spectra (1 Hz) would increase the signal to noise ratio by ~ 1000

FASSST Spectrum of the Classical Weed

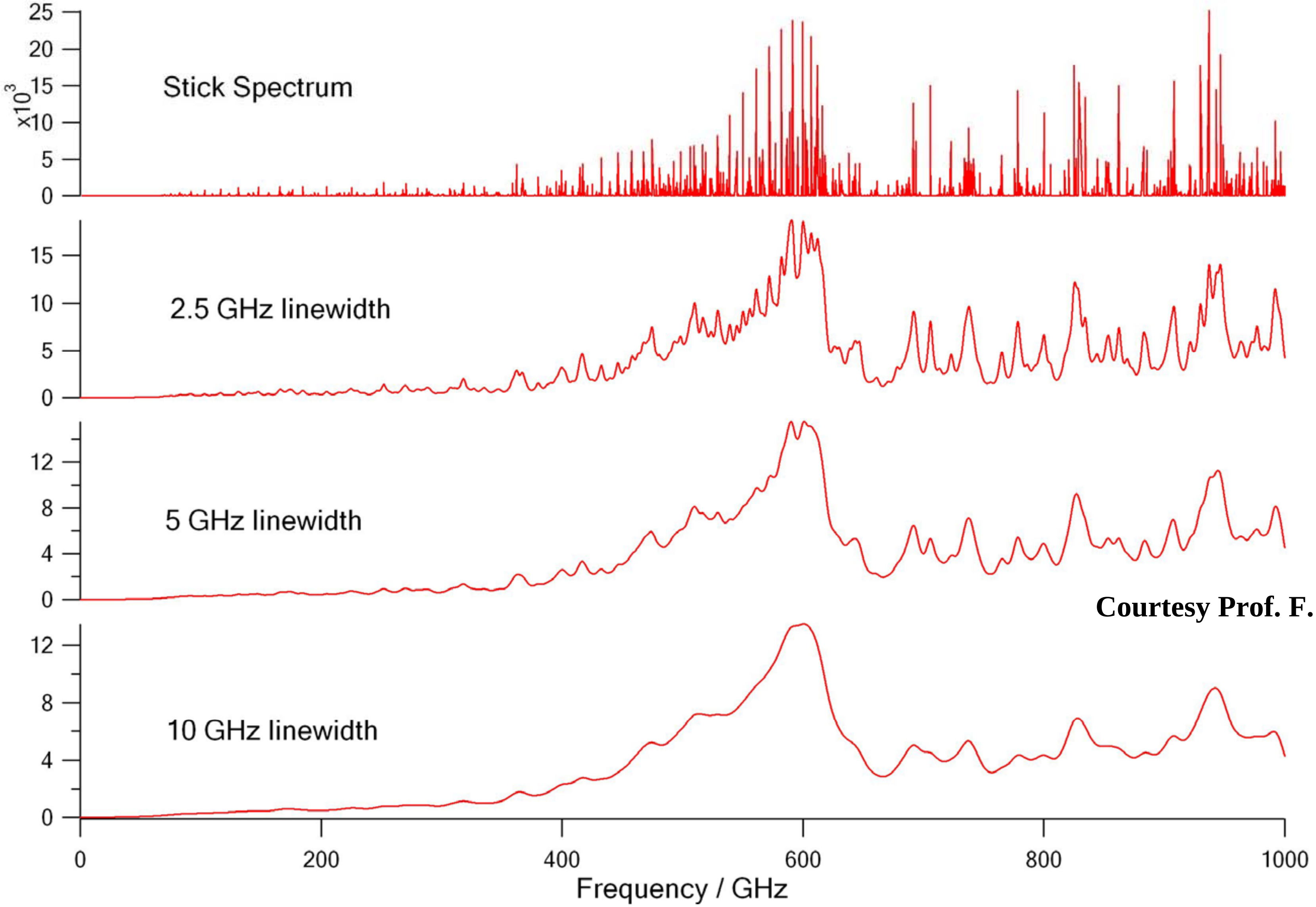
Department of Physics
Microwave Laboratory

Methyl Formate

Courtesy Prof. F. DeLucia

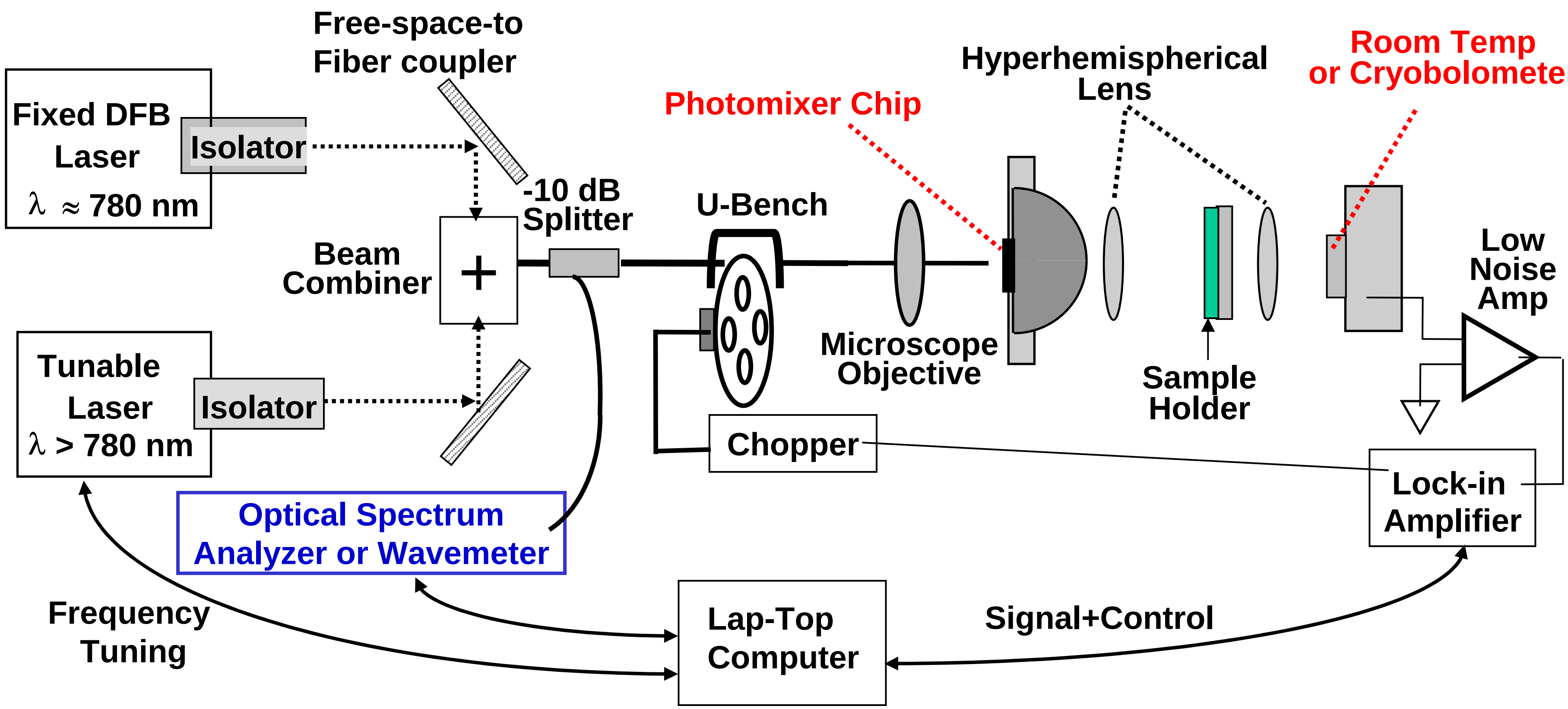


Hydrogen Peroxide Spectrum vs Pressure

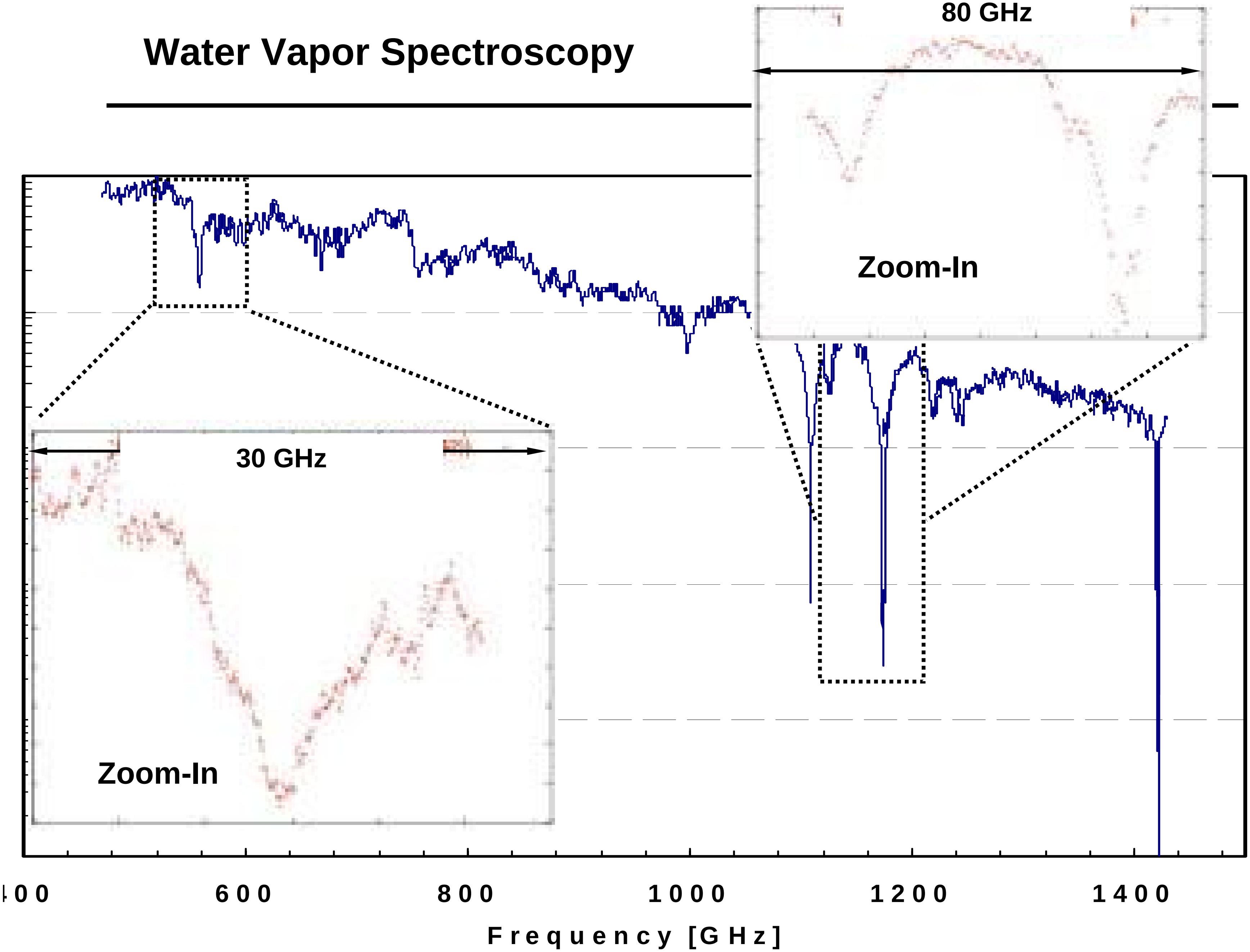


Courtesy Prof. F. DeLucia

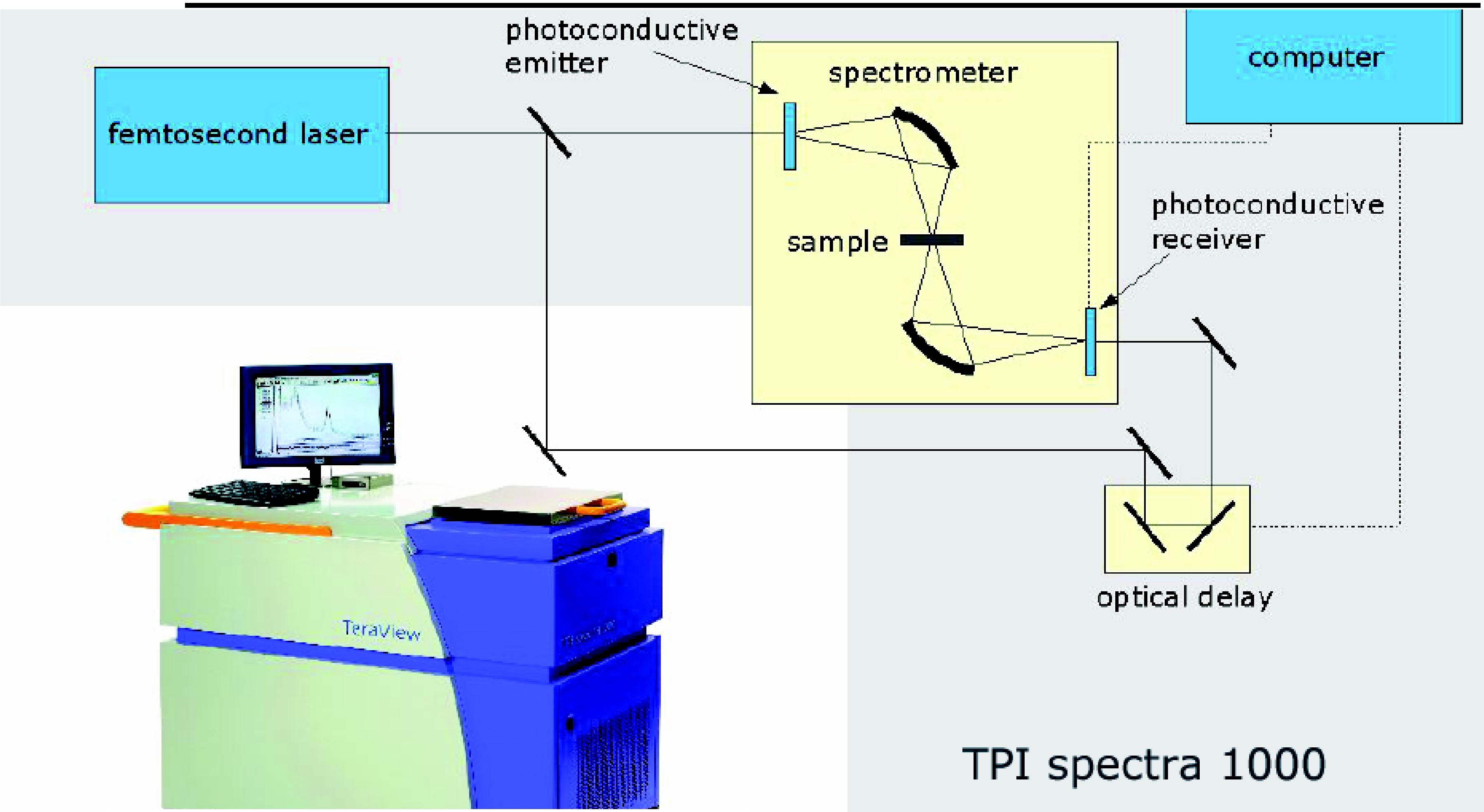
Photomixing Spectrometer: Direct Detection



Water Vapor Spectroscopy



Transmissive THz Time-Domain Spectrometer

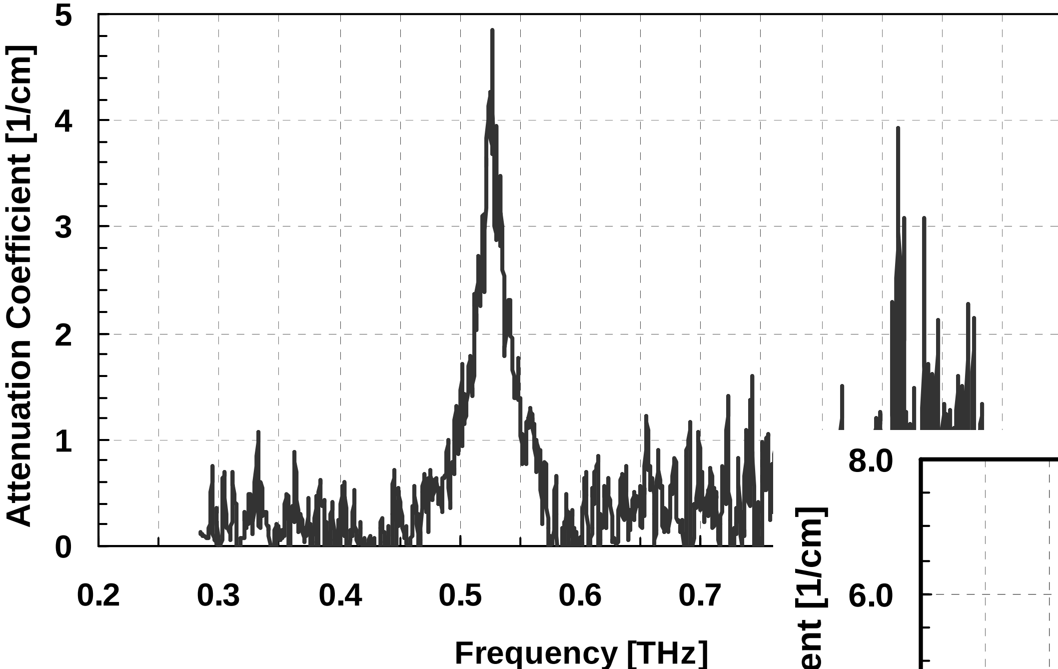


TPI spectra 1000

R&D 100

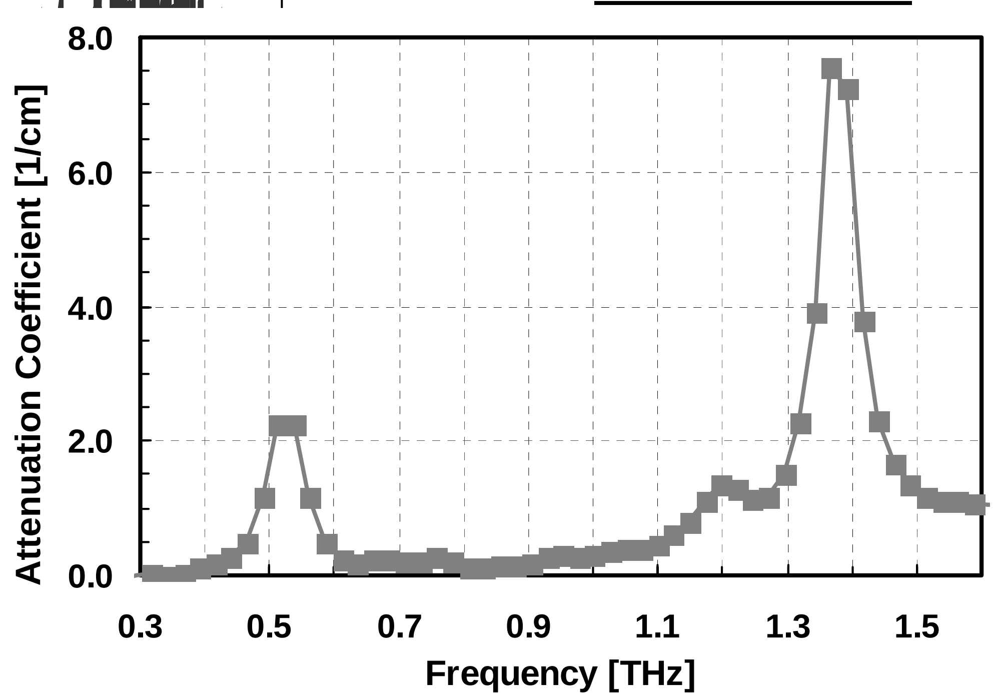
The modified Tera View TPI-1000 THz spectrometer with hybrid scanning mode. Room Temperature.

Photomixer vs Time Domain Spectrometers
(Lactose Monohydrate)

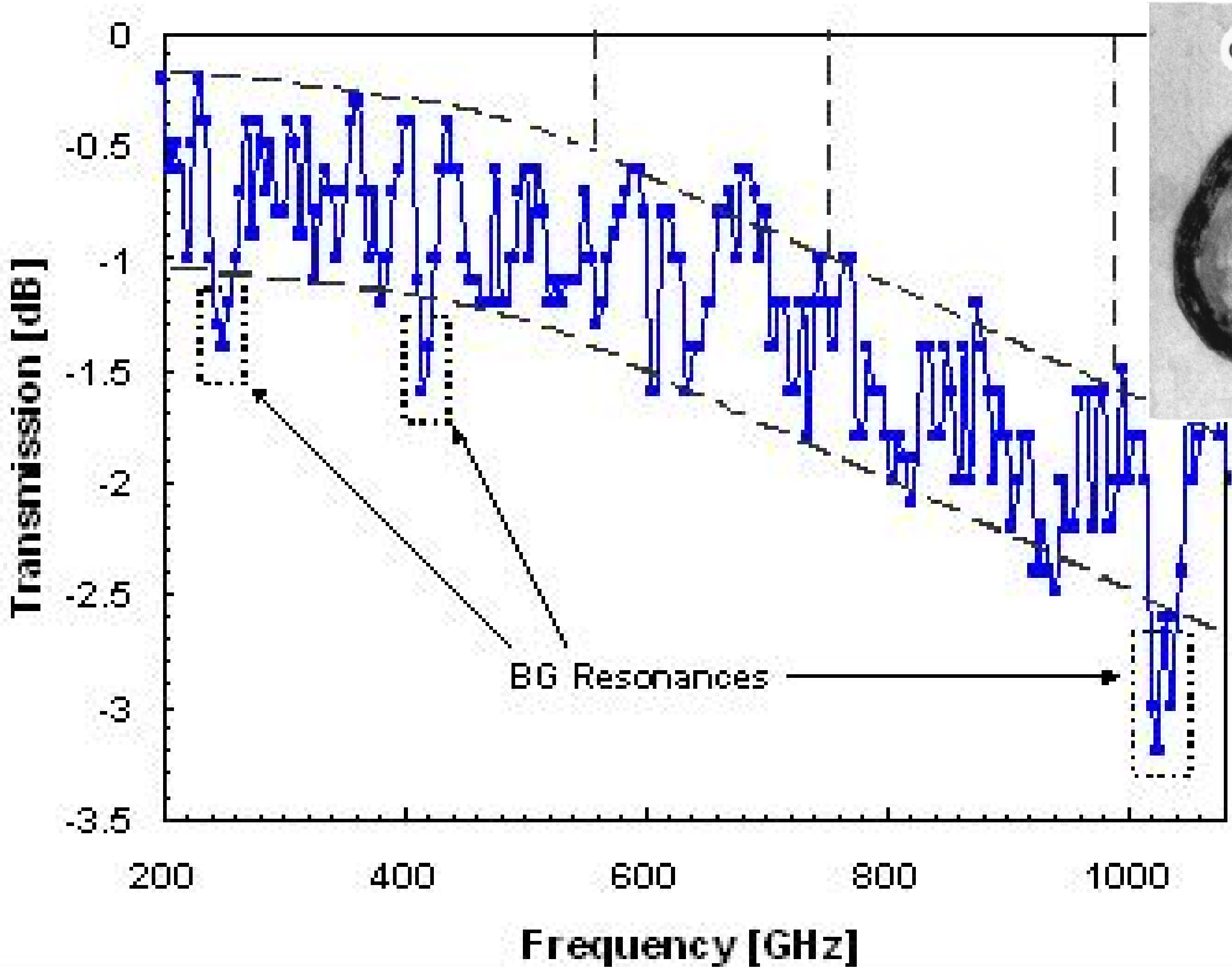


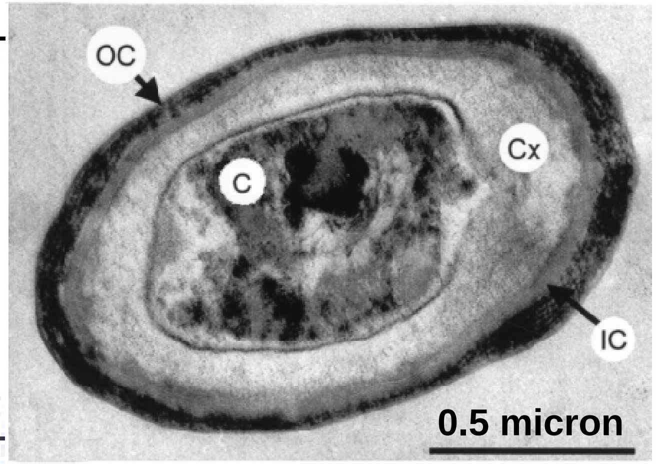
Photomixing

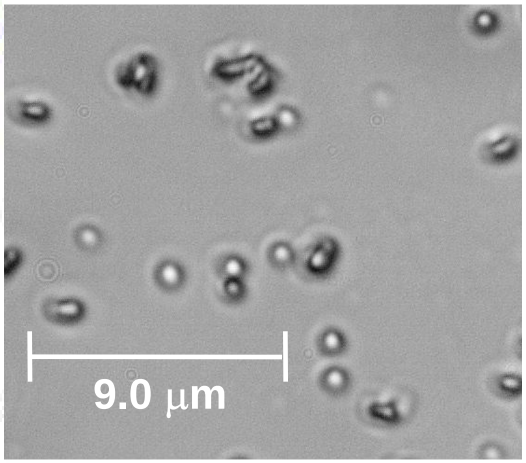
Time Domain



Normalized Transmission: Dilute Bacillus subtilis

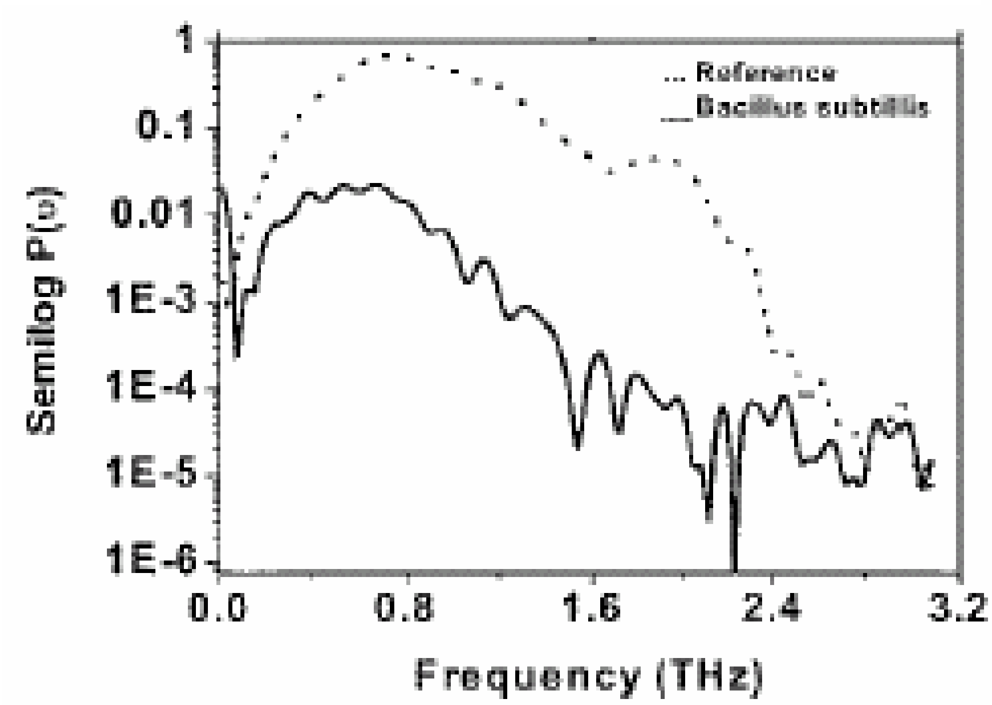


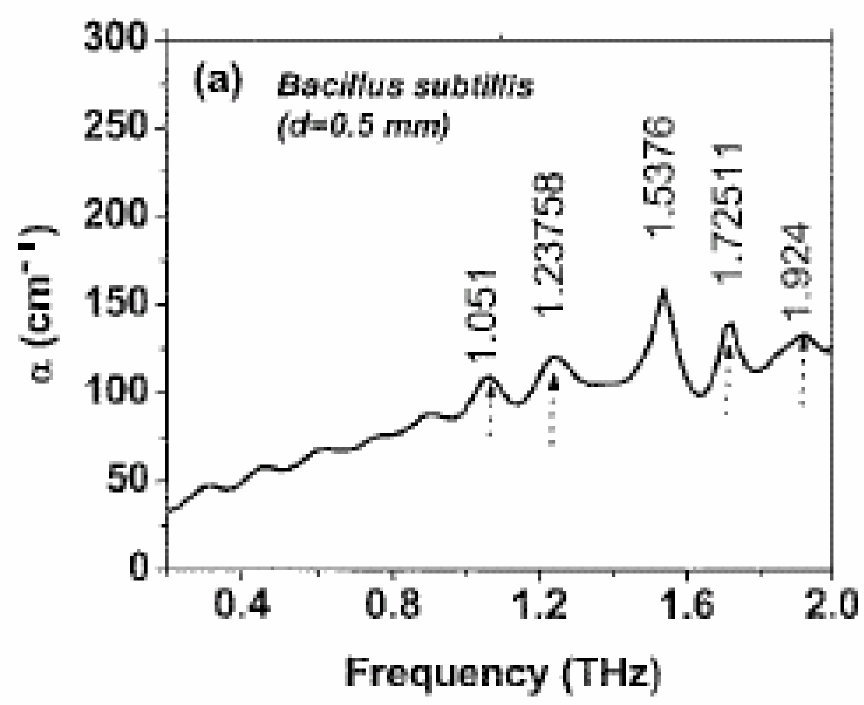




Optical Attenuation Signatures of Bacillus Subtilis in the THz Region," E.R. Brown, J.E. Bjarnason, T.L.J. Chan, A.W.M. Lee, and M.A. Celis, Appl. Phys. Lett., vol. 84 (no 18), p 3438-3440.

Time-Domain Results for Bacillus subtilis

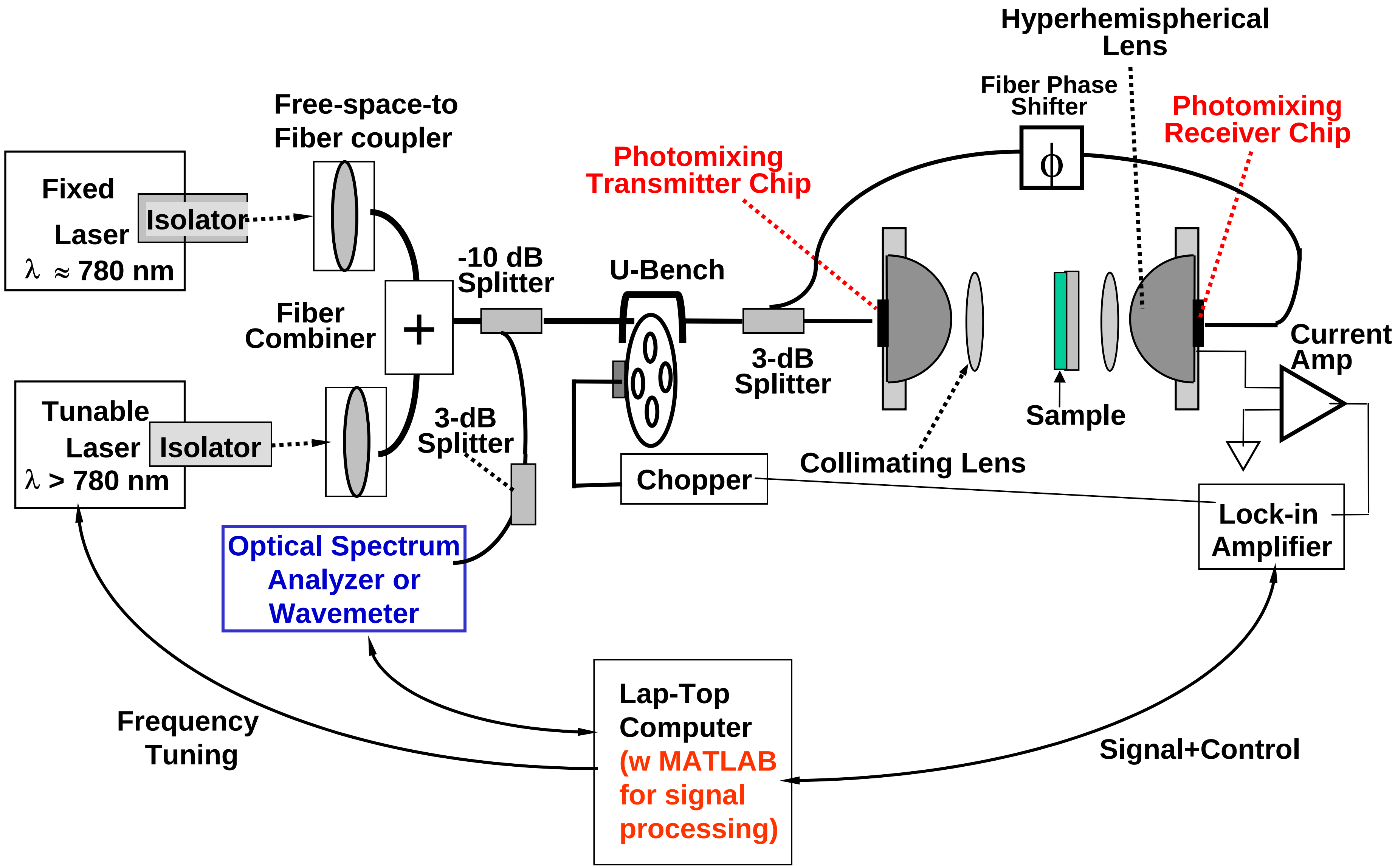




"THz Absorption Spectrum of Bacillus subtilus spores," B. Yu, A. Alimova, A. Katz, And R. R. Alfano, Proc. SPIE paper 5727-3, 2005.

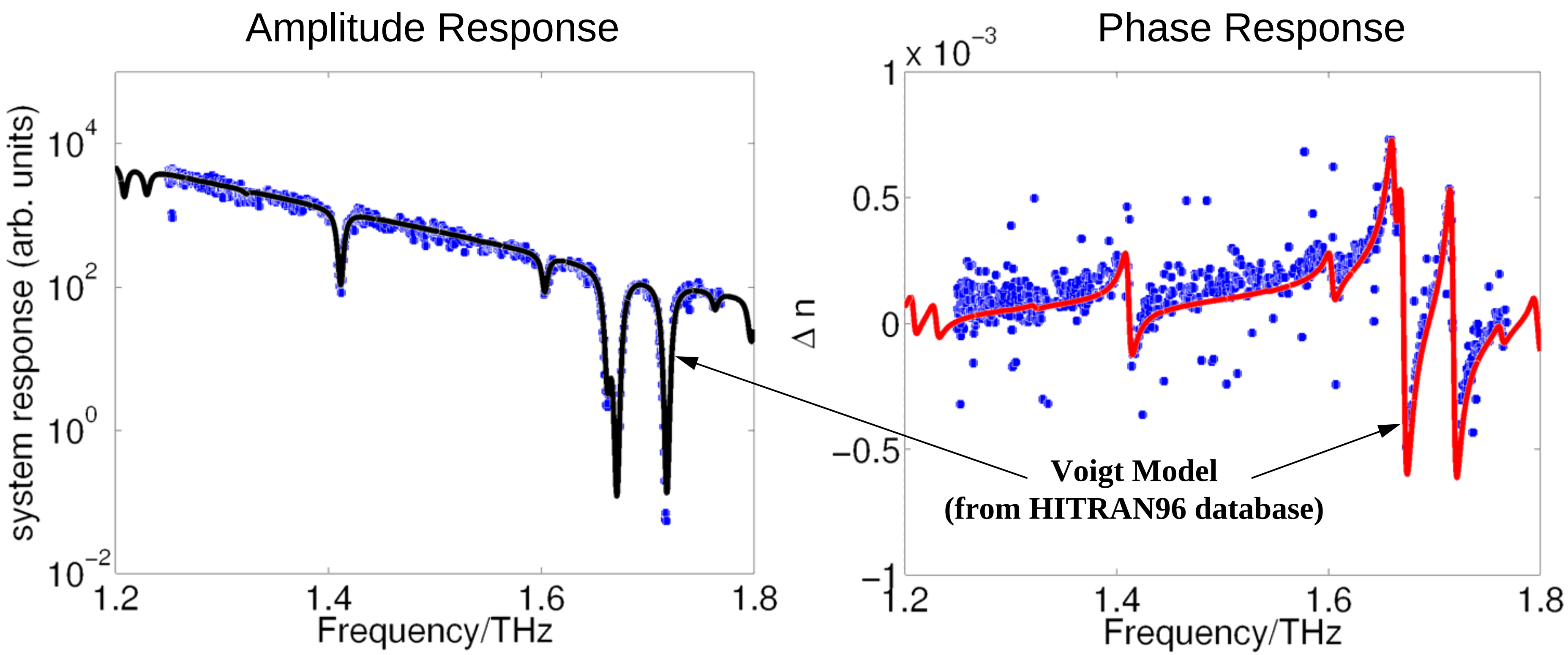
Fewer standing waves,
but much lower resolution
than photomixer spectroscopy

Photomixing Coherent Transceiver



Photomixing Coherent Transceiver Results

Water Vapor at Standard Temperature and Pressure

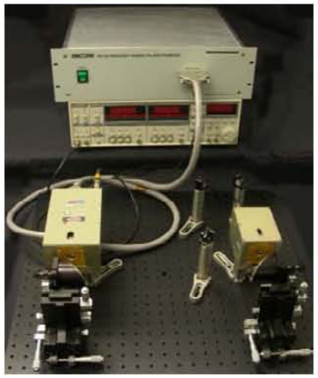


Commercial Photomixing Spectrometer

emcore

PB7100 Frequency Domain Terahertz Spectrometer

PRELIMINARY DATA SHEET | APRIL 15, 2007



The Emcore PB7100 is a simple-to-use turn-key system designed for THz researchers and application developers who need to study materials properties at THz frequencies with high resolution, but who don't want to design and build their own high-resolution THz spectroscopy system. The PB7100 can sweep from 100 GHz to more than 2 THz in a single rapid scan with frequency resolution of 0.5 GHz.

The PB7100 employs precisely tuned semiconductor DFB lasers, advanced photo-mixing source and detector, and sophisticated digital control hardware and software to provide a fully turn-key laboratory THz spectrometer system. The room temperature solid-state homodyne detection technique results in a system NEP of 10^{-12} W/Hz without any need for cryogenics. The highly efficient CW nature of the photomixing source puts all the THz power at the frequency of interest, yielding excellent signal-to-noise ratio of 60 dB-Hz at 1 THz.

And unlike prior time-domain systems requiring complicated mode-locked lasers, the tunable semiconductor laser diodes in the PB7100 can support linear scans or can 'frequency hop' between frequencies of interest to scan specific regions of the spectrum with varying degrees of resolution. The separate source and detector heads may be configured to make measurements in transmission or reflection configurations.

Applications

Threat signature characterization

- **Explosives**
- **Biological agents**
- **Chemicals**

Microwave and THz Spectroscopy

- **Transmission mode**
- **Reflection mode**

THz Applications Development

Features and Benefits

Full turn key system – nothing else to buy to start taking THz measurements

Continuous rapid scanning from 100 GHz to over 2 THz

Integrated digital controller with data collection software and computer (included)

'Frequency Hopping' function

Electronic chopping: 10Hz to 50kHz

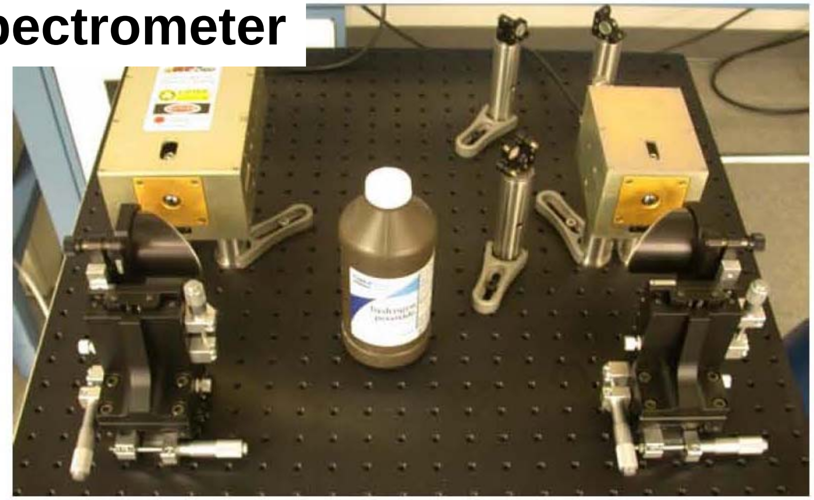
Room Temperature Solid State Detection

Performance Highlights

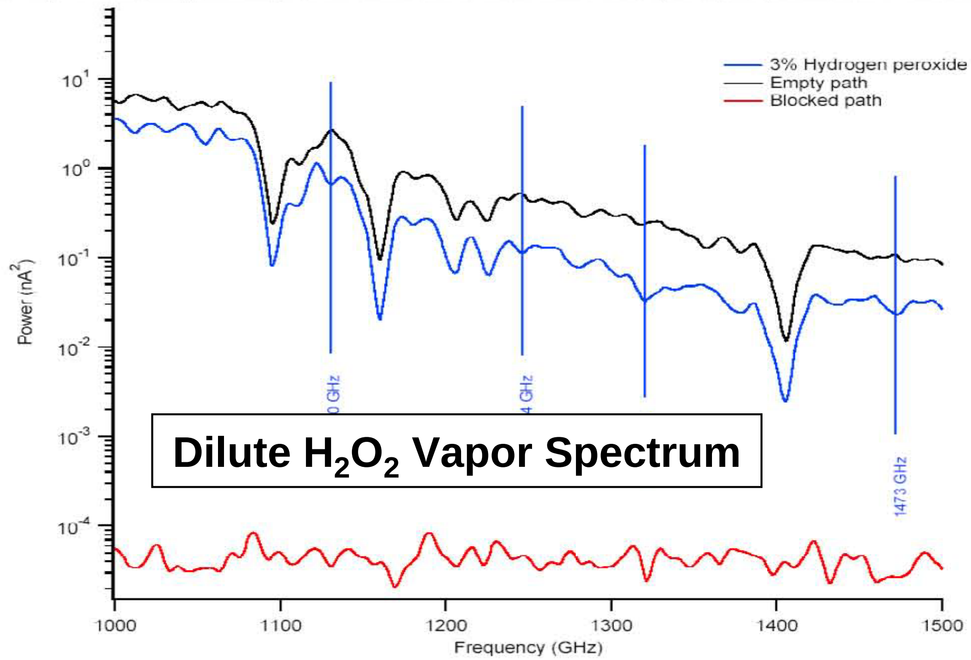
		Min	Typical	Max	Units
Frequency Tuning Range		100	–	2000	GHz
Spectral Purity		0.010	0.015	0.025	GHz
Frequency Resolution		0.25	0.50	–	GHz
THz Output Power	100 GHz	2	4	–	uW
	500 GHz	1	2	–	uW
	1000 GHz	0.5	1	–	uW
	1500 GHz	0.1	0.5	–	uW
Detector Sensitivity (NEP @ 1000 GHz)		10^{-12}	10^{-11}	10^{-10}	W/Hz
Electronic Chopping Frequency		10	25,000	50,000	Hz

Commercial Photomixing Spectrometer

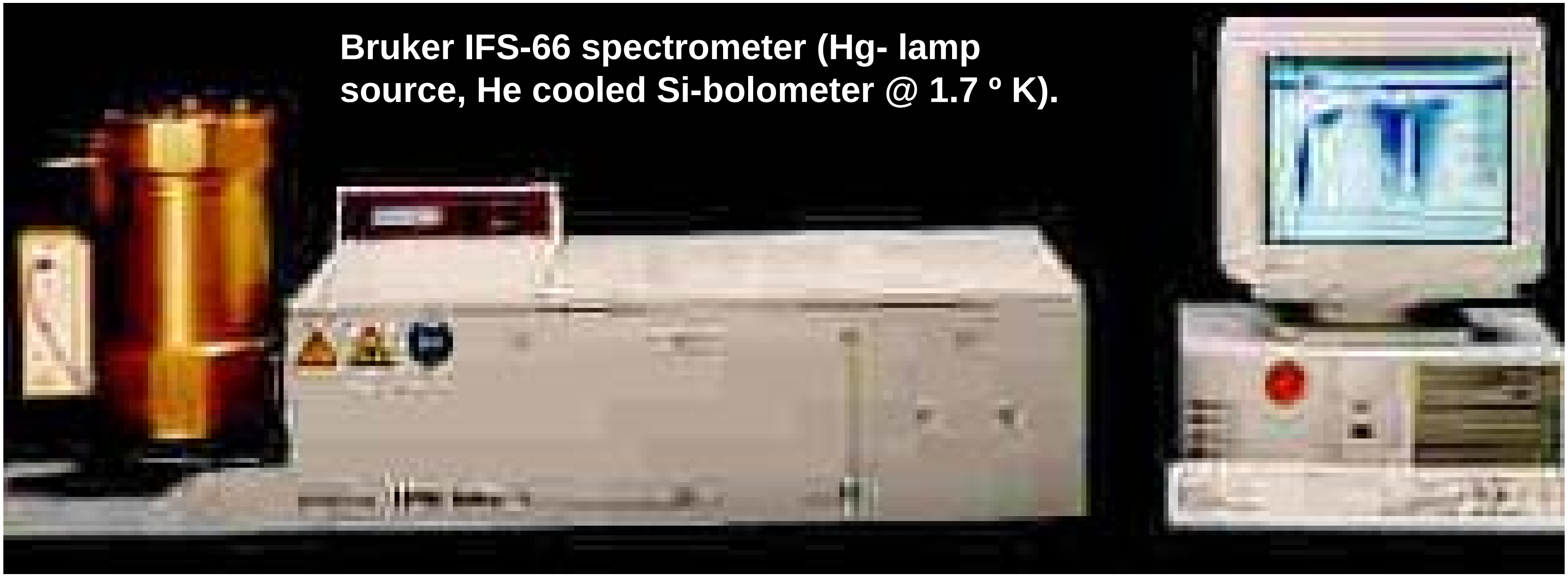
Photomixer Source Module



The PB7100 Frequency Domain THz Spectrometer used to detect hydrogen peroxide vapor by measuring through the bottle of household 3% hydrogen peroxide. Plot below.



THz Fourier Transform Spectroscopy



Bruker IFS-66 spectrometer (Hg- lamp source, He cooled Si-bolometer @ 1.7 º K).

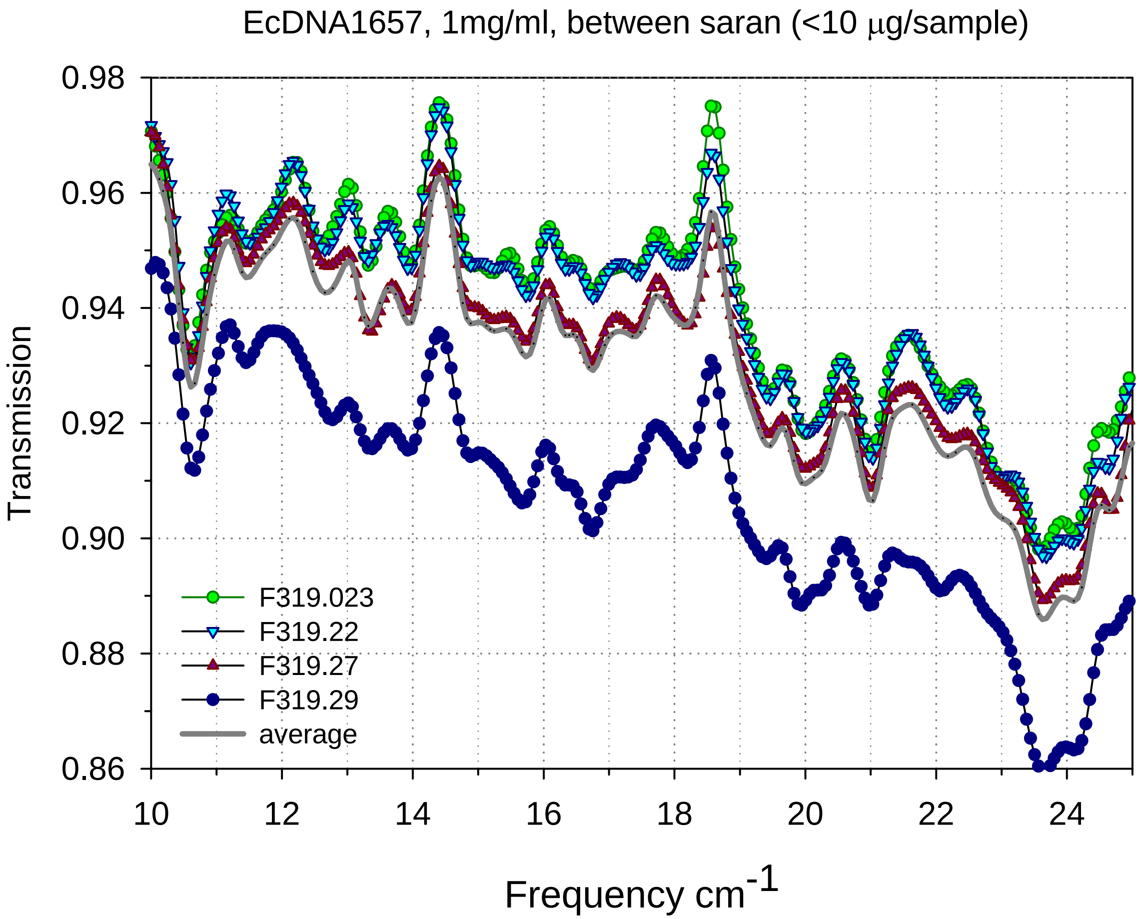
The estimated energy relaxation time (From the width of the vibrational modes) ~$7 \cdot 10^{-11}$ s **requires the spectral resolution for resonance feature measurements of ~0.25-0.3 cm^{-1} (7.5 to 9.0 GHz)**

(courtesy Dr. T. Globus, Univ. Virginia)

Experimental Results for E. Coli DNA

***DNA sample** (concentration 1 mg/ml or 0.1%) between two Saran films.*

Courtesy: Dr. T. Globus, Univ Virginia



Resonance structure is sensitive to orientation of a sample relative to the electric field of radiation. The resonance around 14 cm^{-1} is especially sensitive to the orientation of DNA molecules in the sample. Most samples of *E. coli* DNA show an absorption peak at 14 cm^{-1}. Only these spectra were used for averaging.

Experimental Results for E. Coli DNA (cont)

DNA sodium salt from *Escherichia coli* dissolved in deionized H_2O at concentrations in the range of 0.01-1 mg/ml (0.001-0.1%) with less than 100 ng in the sample (< 10 μl of solution)

(from T. Globus, T. Khromova , B. Gelmont , D. Woolard , and L. K. Tamm,, SPIE 2006, Biomedical Optics Symposium, San Jose, Jan. 2006)

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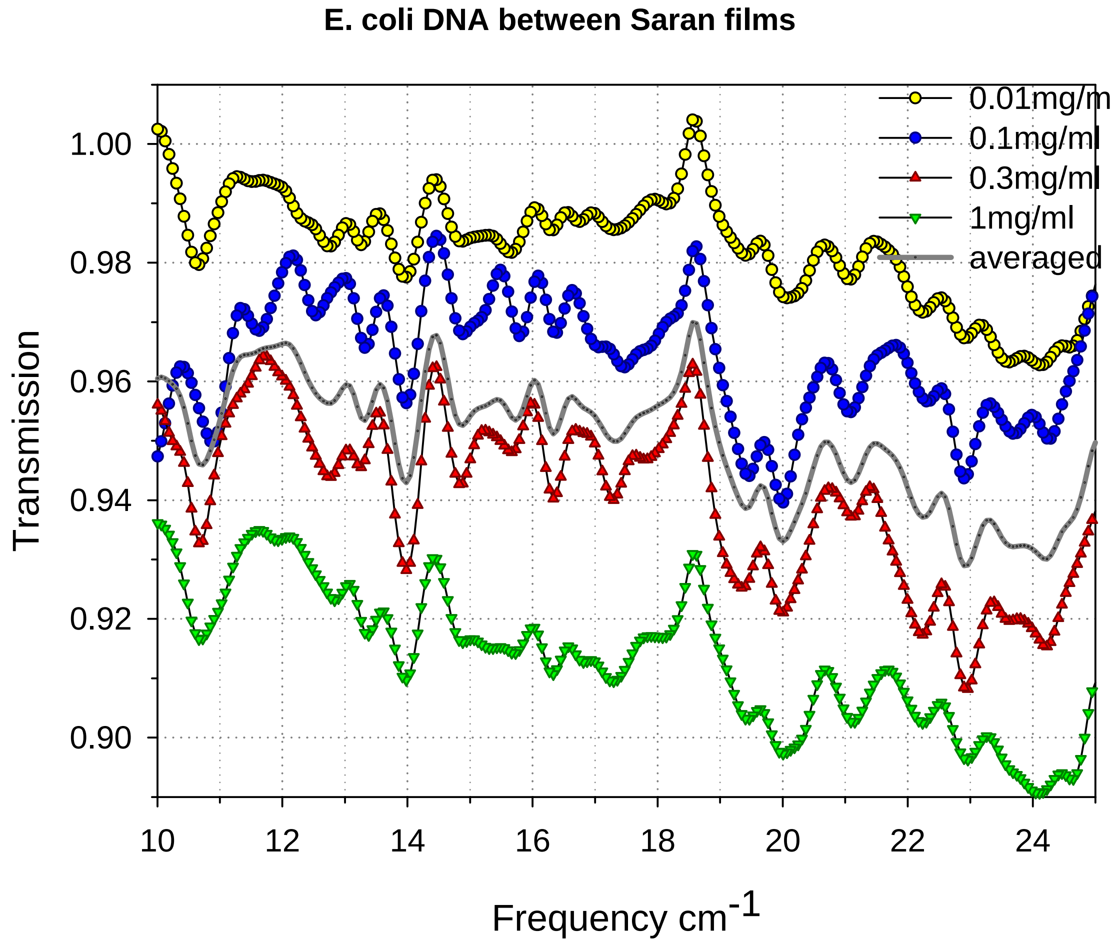
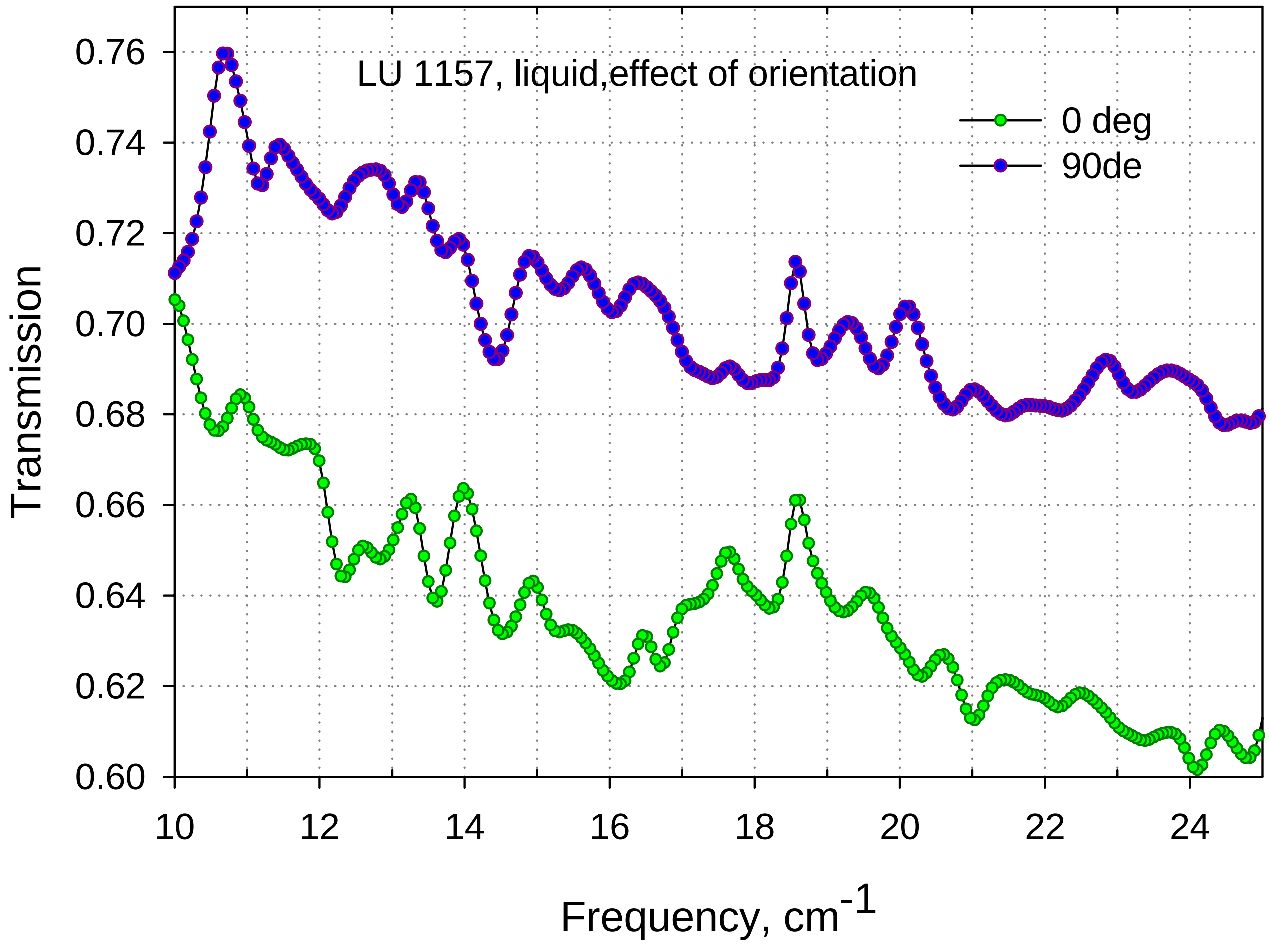


The average spectra obtained at four different concentrations in between Saran films.. A rough estimate indicates that the smallest concentration (0.01 mg/ml) is sufficient to form a monolayer of DNA on the surface of the substrate.

Experimental Results for Protein (cont)

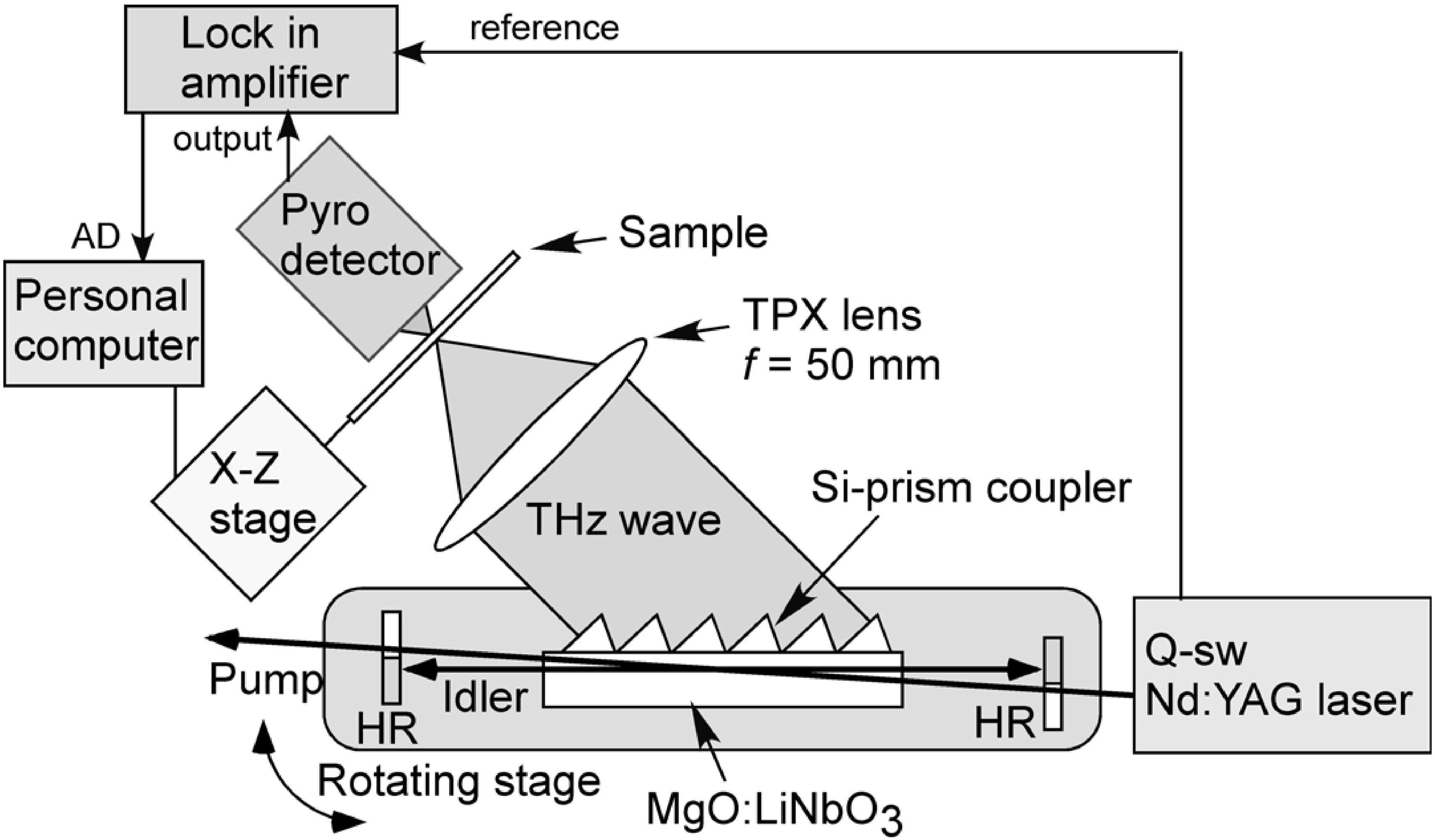
Orientation effects in spectra of unfolded protein Lysozyme

(from T. Globus, T. Khromova , R. Lobo, D. Woolard , N. Swami , and E. Fernandez, Proc. SPIE, v. 5790, p.54-65, 2005)



The interaction between bio-and substrate material is significant and likely controlled by substrate surface charges. This interaction causes the first monolayer of biomolecules to adsorb to the substrate in specific orientations.

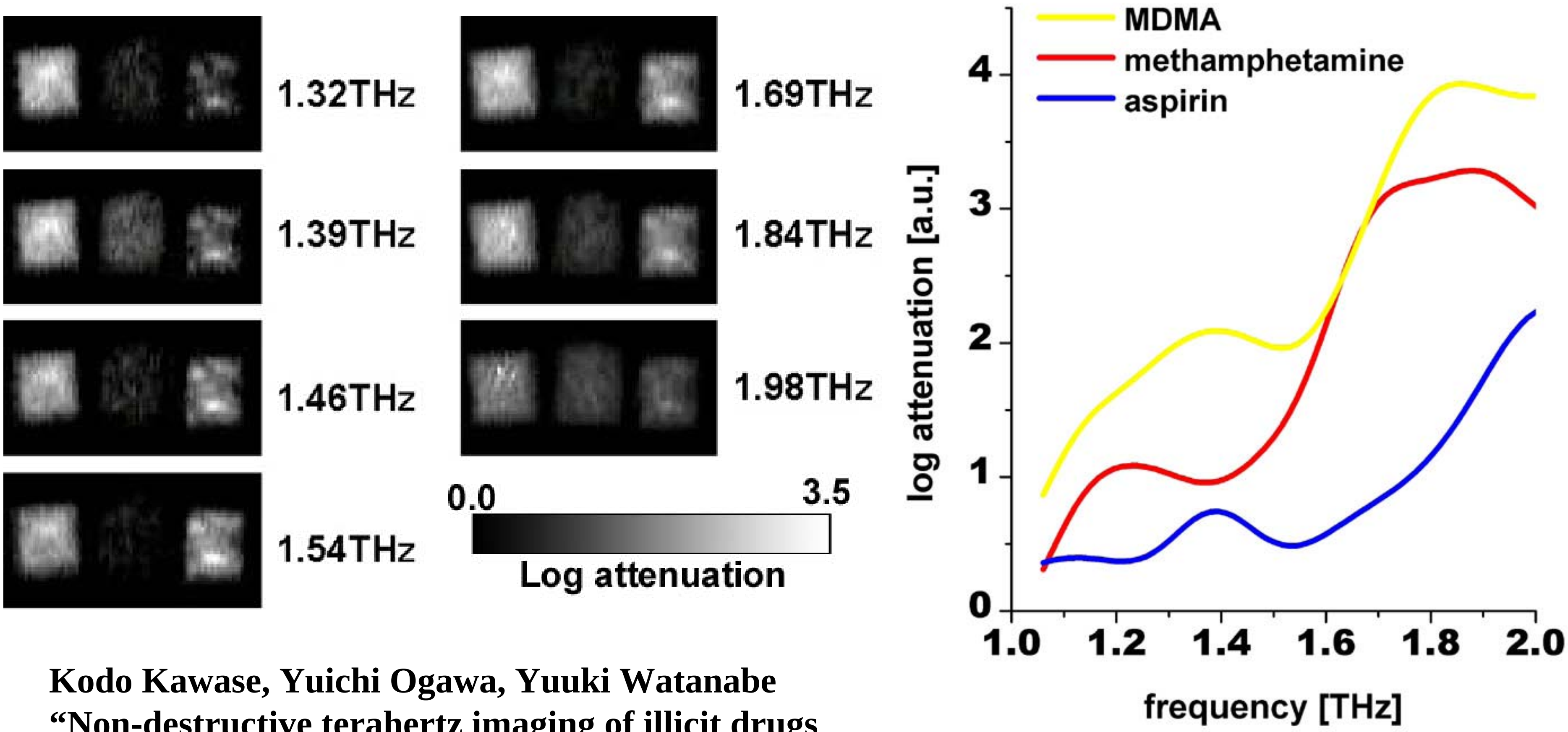
THz Parametric Difference Frequency Generation



Kodo Kawase, Yuichi Ogawa, Yuuki Watanabe "Non-destructive terahertz imaging of illicit drugs using spectral fingerprints", 6 October 2003 / Vol. 11, No. 20 / OPTICS EXPRESS 2549

Multi-Color THz Imagery of Drugs

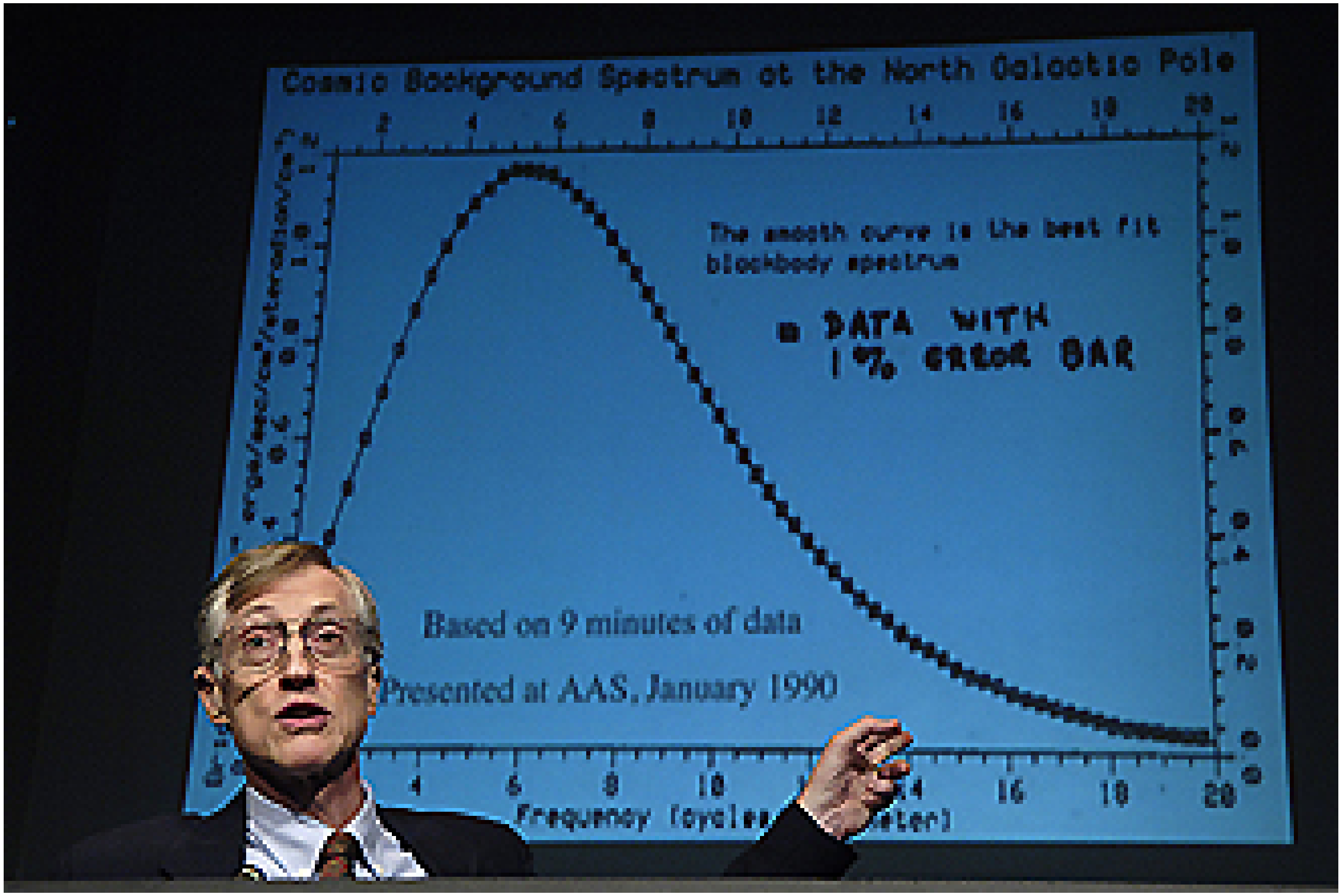
Seven multispectral images



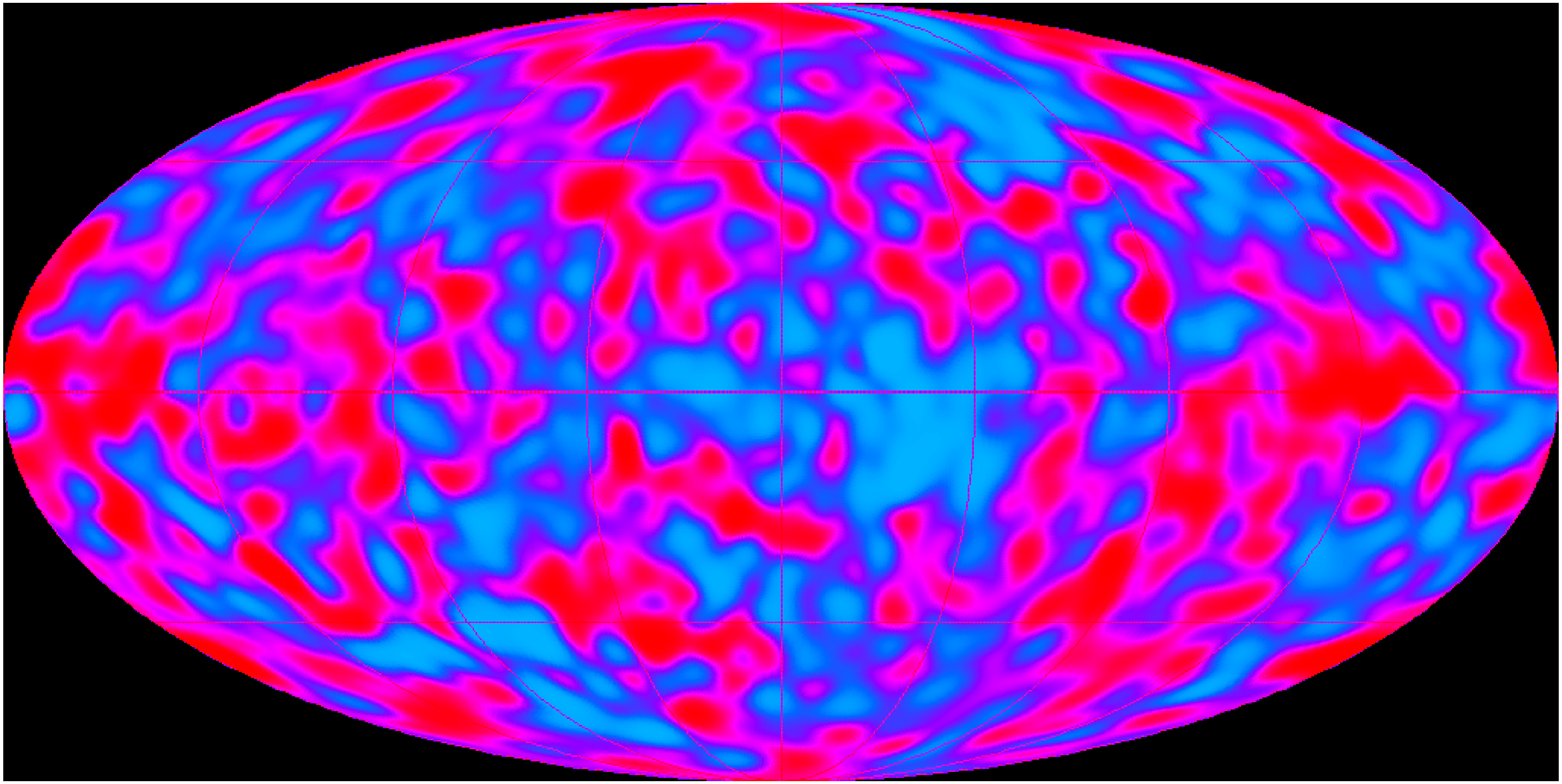
Kodo Kawase, Yuichi Ogawa, Yuuki Watanabe "Non-destructive terahertz imaging of illicit drugs using spectral fingerprints", 6 October 2003 / Vol. 11, No. 20 / OPTICS EXPRESS 2549

The First Nobel Prize for the THz Field !

For: "their discovery of the black body form and anisotropy of the cosmic microwave background radiation".



The Universe Through THz Eyes



T_{ave} = 2.73 K, $\Delta T \sim 30\ \mu K$

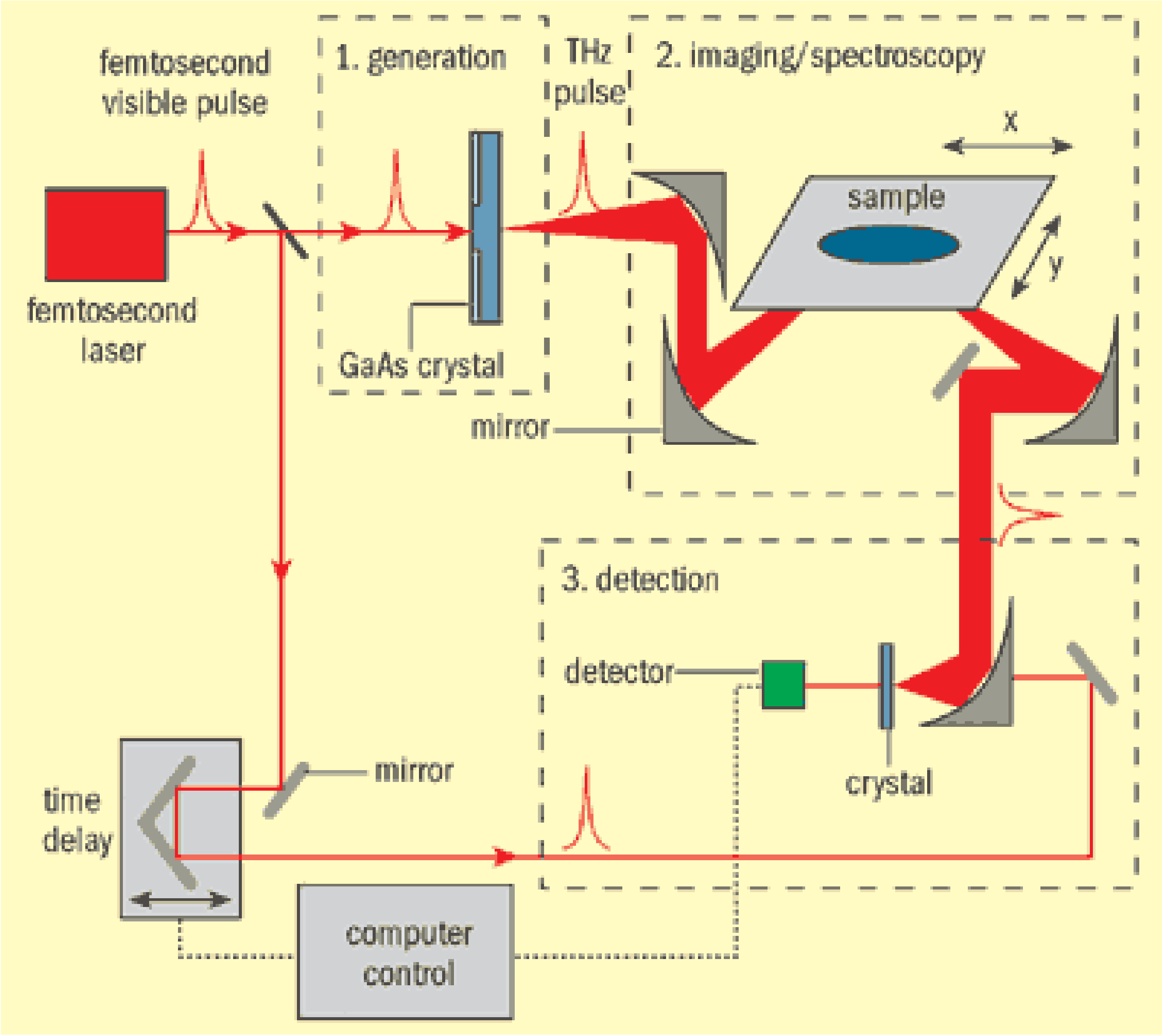
THz Spectral-Spatial Sensing

- With the advent of THz sources with high peak power and spatial coherence, it becomes possible to detect in select THz sub-regions and select spatial regions.

- First spectral-spatial “maps” were generated by radio astronomers using motion of earth to steer THz beam through interesting regions

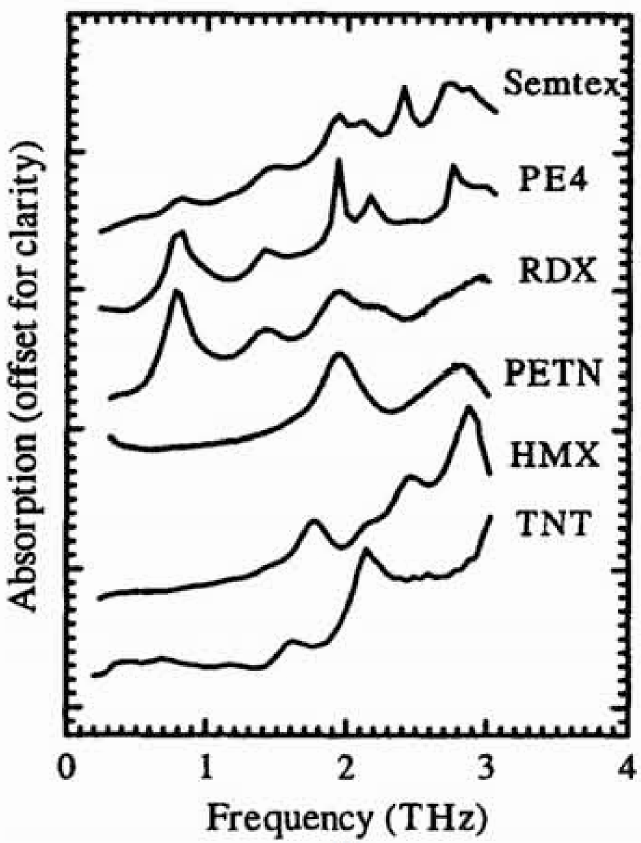
- Given high SNR of ultrafast photoconductive emitters, we now can engineer spectral-spatial imagers using a single pixel
  - time-domain system in reflection
  - gated THz radar using a fast rectifier as envelope detector

Reflective Time-Domain Spectrometer System

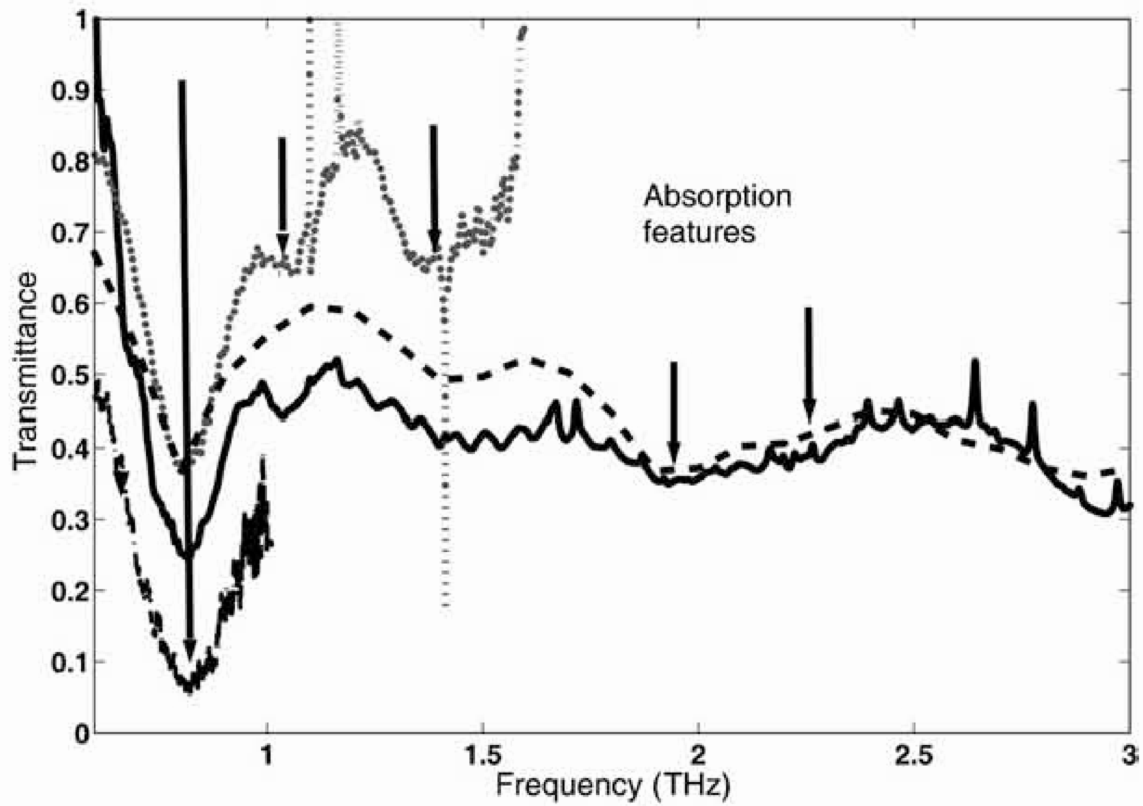


THz Spectra of Solid Explosives

Time-Domain Spectra of Explosives

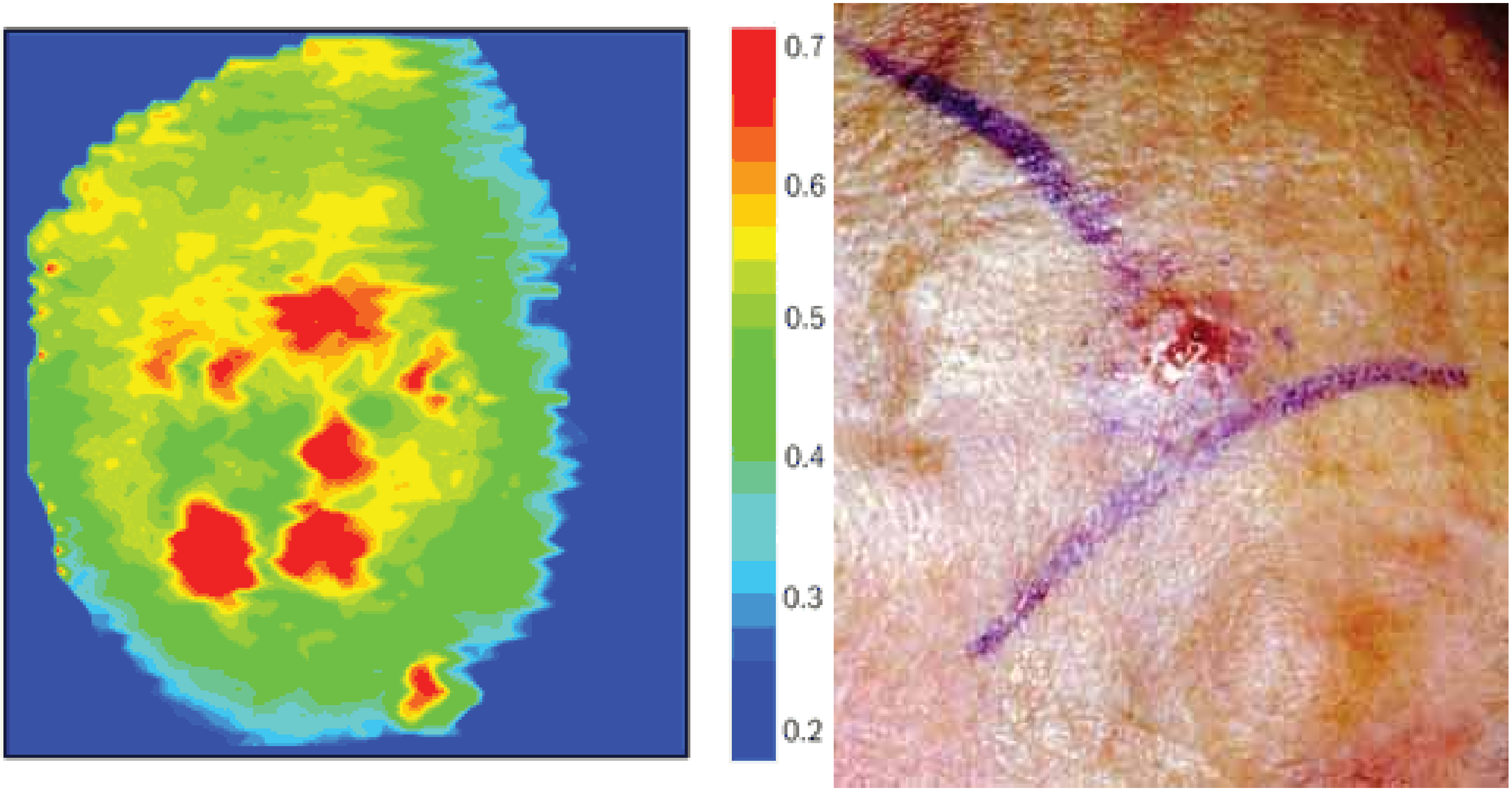


Time-Domain vs FTIR on RDX



[**John F Federici, Brian Schulkin1, Feng Huang, Dale Gary1,Robert Barat, Filipe Oliveira and David Zimdars, Semicond. Sci. Technol. 20 (2005) S266–S280]**

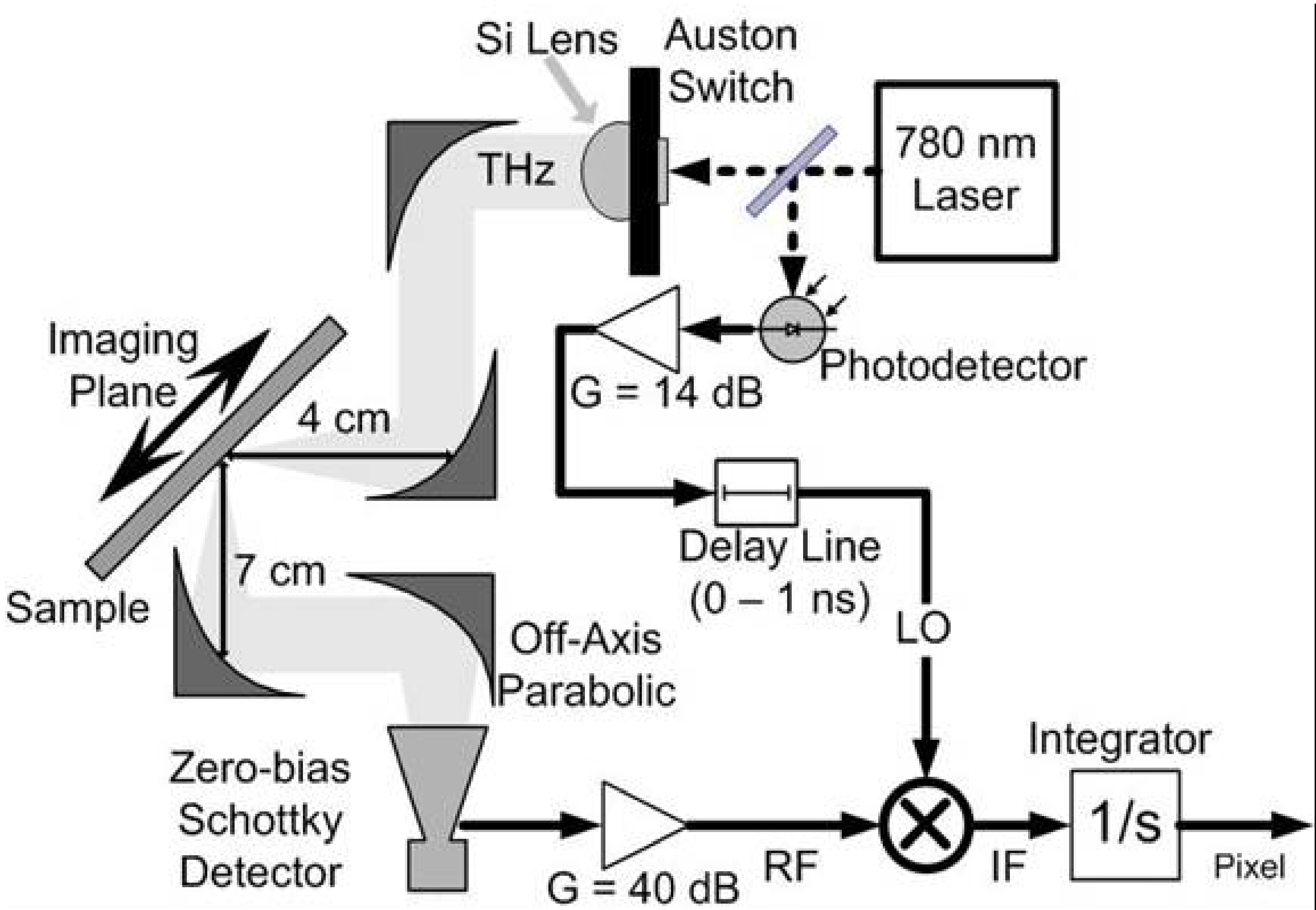
Time Domain: Medical Imaging



Terahertz image of a skin cancer (Basal cell carcinoma) on a patient's forehead, taken using Teraview's medical-imaging equipment. The red hotspots in the image indicate regions of tumour, and the green/yellow regions indicate normal healthy tissue

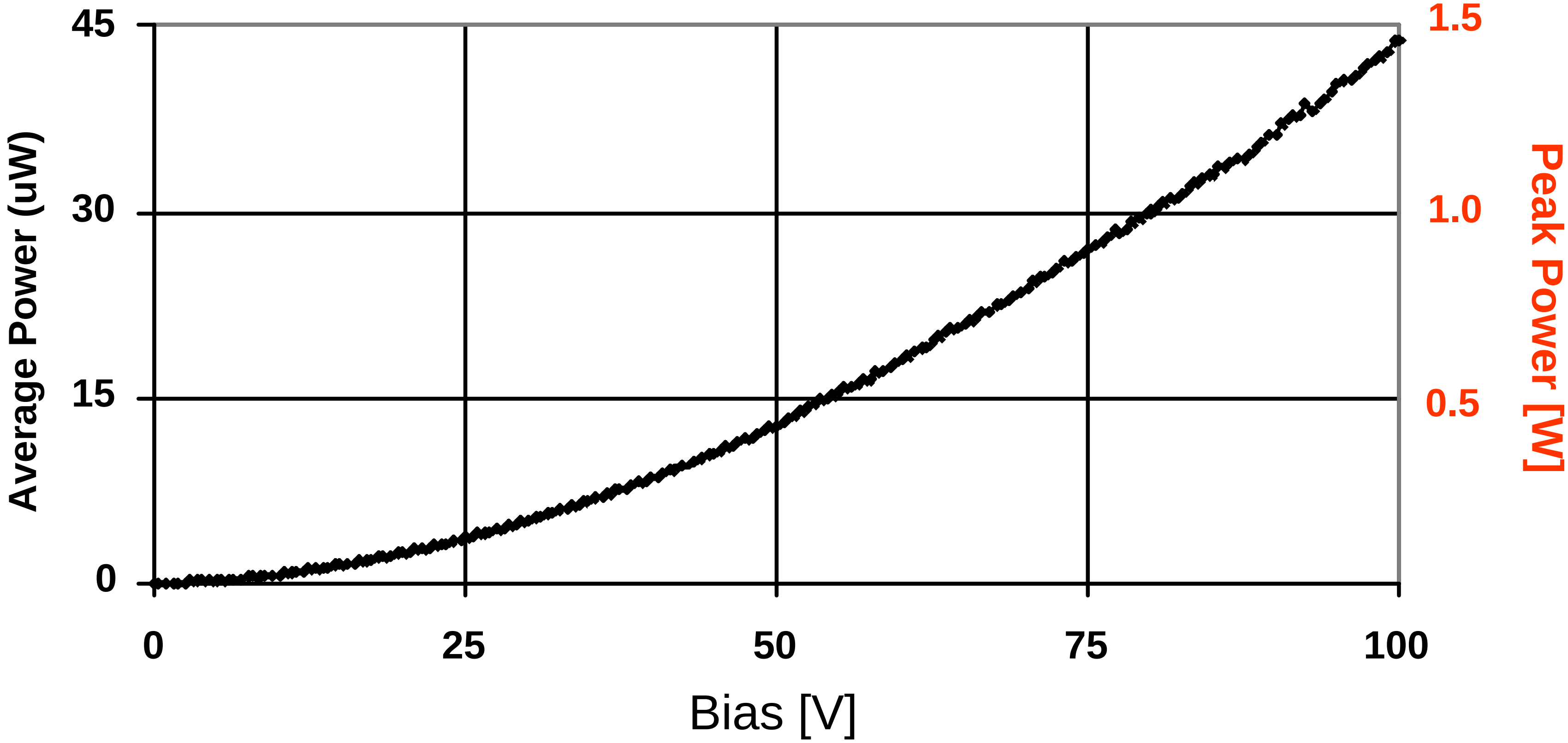
http://optics.org/cws/article/research/9937

THz Pulse Gated Radar



Z.D. Taylor, R.S. Singh, E.R. Brown, J.E. Bjarnason, M.P. Hanson and A.C. Gossard
"A Reflection Based Pulsed THz Imaging System with 1 mm Spatial Resolution," IMS 2007 Proc., Paper WEP2A-11

Photoconductive Switch Performance

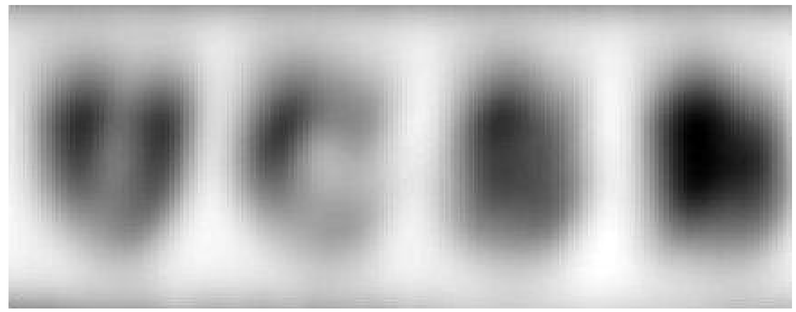


"Resonant-optical-cavity photoconductive switch with 0.5% conversion efficiency and 1.0W peak power," Z. D. Taylor, E. R. Brown, J. E. Bjarnason, M. P. Hanson, and A. C. Gossard Optics Letters, Vol. 31, Issue 11, pp. 1729-1731 (2006

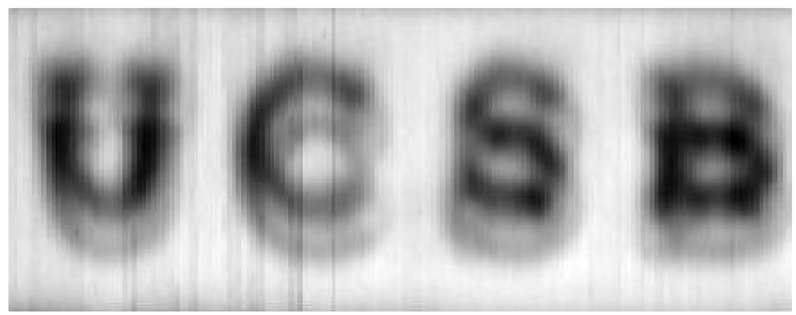
Gated Radar Imager Resolution

Visible Image

Passband Center Frequency



100 GHz

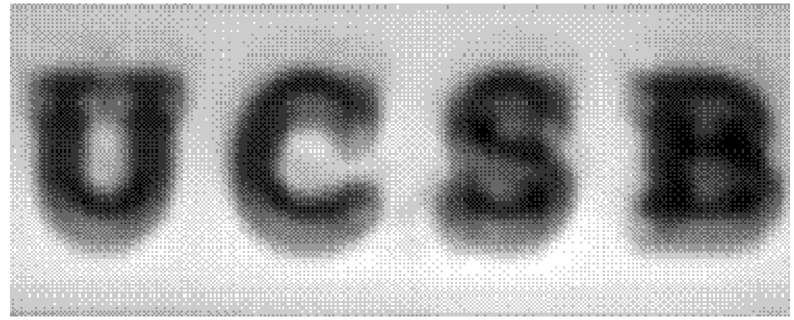


350 GHz

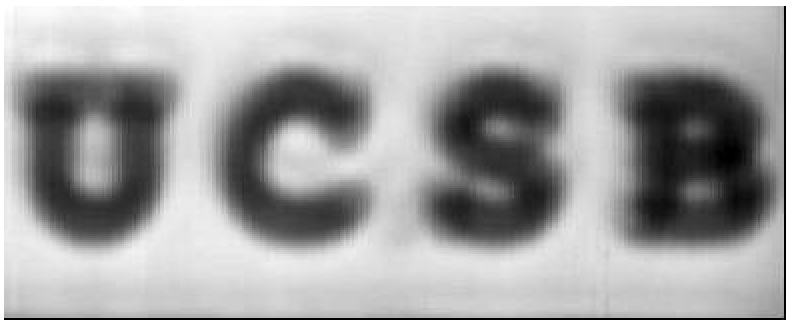
600 GHz

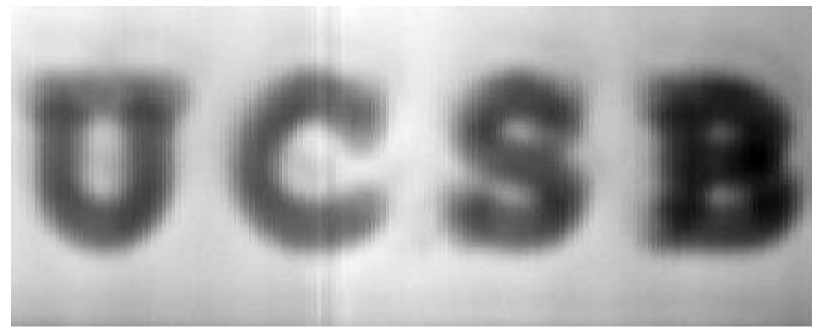
600 GHz Imaging Through Clothing

Visible Image



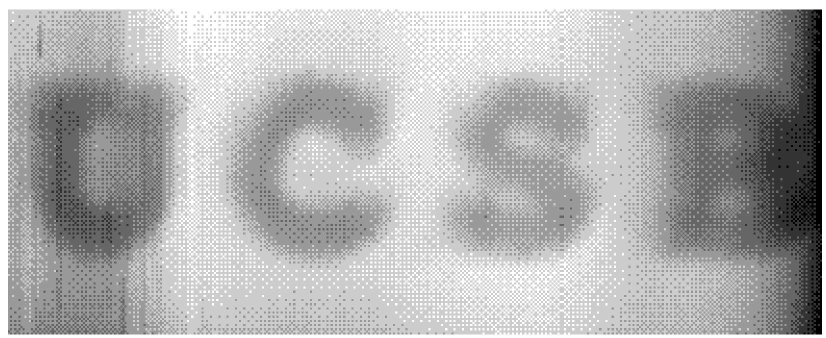
1 Layer





4 Layer

5 Layer

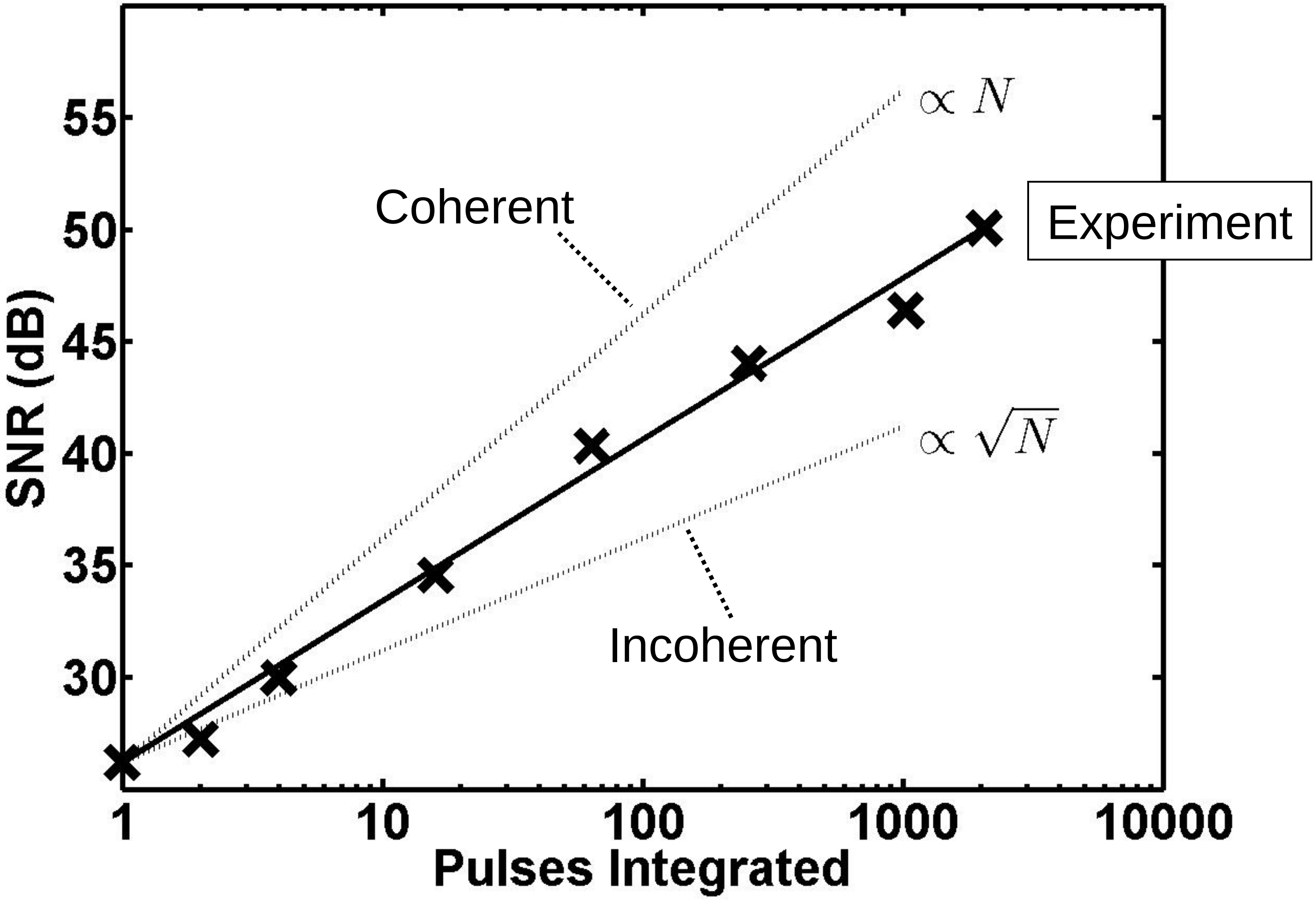


6 Layer

**Each Layer
(1 mm thick Denim)**

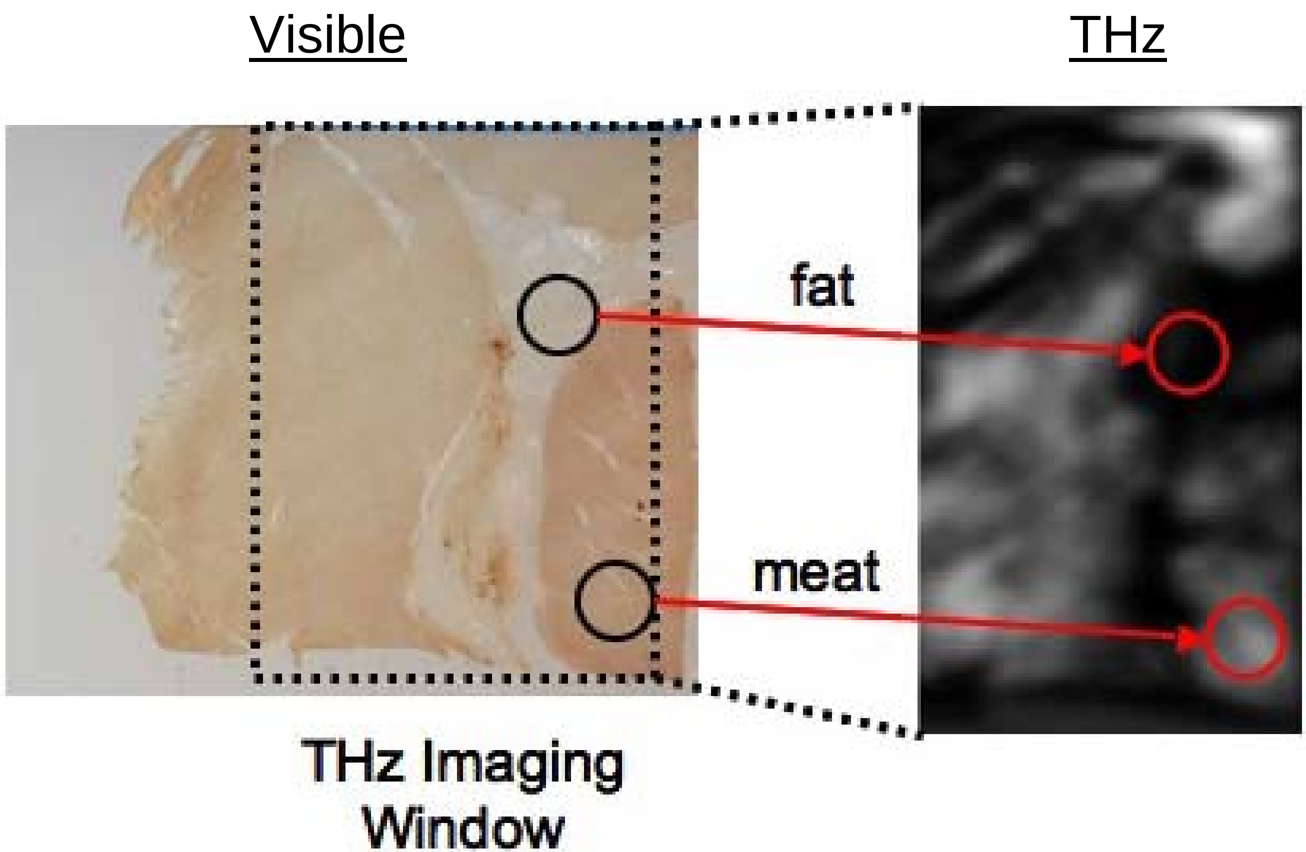
Z.D. Taylor, R.S. Singh, E.R. Brown, J.E. Bjarnason, M.P. Hanson and A.C. Gossard
"A Reflection Based Pulsed THz Imaging System with 1 mm Spatial Resolution," IMS 2007 Proc., Paper WEP2A-11

Signal-to-Noise Ratio vs Pulse Integration



Soft Tissue Imaging in Reflection @600 GHz

Prosciutto Slice



(Courtesy: Z.D. Taylor, UCSB)

Summary: Potential THz Applications

Spectroscopy

Standoff
- Standoff C/B Detection
- Standoff Explosives Detection

Point
- Point C/B Detection
- Point Explosive Detection
- Pharmaceutical
- Medical

Imaging

Standoff
- Force Protection (CWD)
- THz Radar (3D Imaging)
- Multispectral Imaging
- Seeing Through Walls
- Search and Rescue
- UAV - All Weather Reconaissance
- Weapon Guidance
- Landing Aids
- Space Imaging

Point
- Portal CWD
- Non-Destructive Inspection
- Medical Tomography (3D Imaging)

Communicatons

Standoff
- Tactical Data Links (All Weather & Dust)

Point
- Covert Comm

- For which does THz offer best new capabilities?
- Which would develop the key technology pieces common to most other applications?

Courtesy:
Dr. Mark Rosker

Summary: THz Advantages/Challenges

Spectroscopy

Standoff

- Undetermined signature specificity for gases at atmosphere pressure and condensed phase

Point

- Highly specific signatures for low pressure gas phase
- Extremely sensitive to presence of H_2O

Imaging

Standoff

- Non-ionizing propagation through opaque materials
- Favorable aperture size
- Favorable FPA size
- High radar resolution
- Coherent detection
- Aperture size/propagation tradeoff with frequency
- FPA arrays unavailable
- Very long acquisition time

Point

- Spectral imaging possible
- FPA arrays unavailable
- Long acquisition time

Communicatons

Standoff

- Superior propagation through fog, clouds, dust
- Range limited by absorption
- ESA arrays unavailable

Point

- Extremely high absorption possible
- ESA arrays unavailable

Common to All

- Component Availability/Cost
  - Solid-state sources
  - Detectors
- Integration
- Calibration / Measurement
- Design Tools

Courtesy:
Dr. Mark Rosker

- Advantages
- Challenges