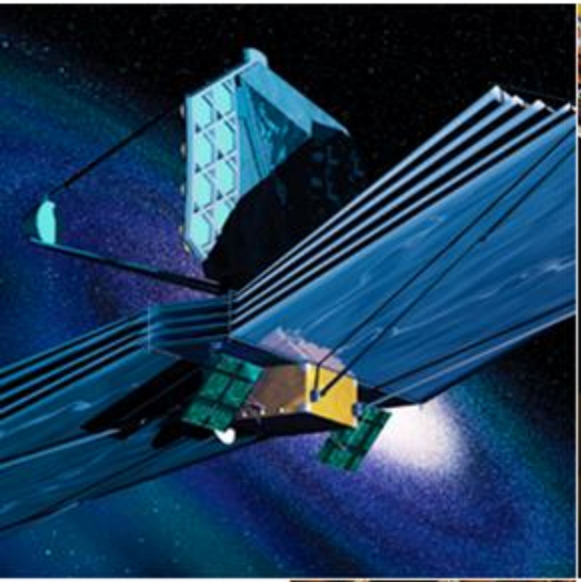


Terahertz Materials Characterization in Extreme Environments

Emerging Tools for Materials Research

David R. Daughton
Applications Scientist

Materials Characterization Systems

Magnetometers (VSM/AGM)

Measure magnetic properties:
- Hysteresis M(H) loops
- FORC curves
- Temperature dependencies

Permanent Magnets
High Density Recording Media
Mineral Magnetism

Hall Effect Measurement Systems (HMS)

AC/DC measurements:
- Hall mobilities
- Carrier concentration
- Carrier type

Thermoelectrics
Solar Cells
HEMTS

Probe Stations

Measure electrical properties of devices and materials in temperature-controlled environment

Nanowires
Magnetoresistance
Organic electronics

THz Systems

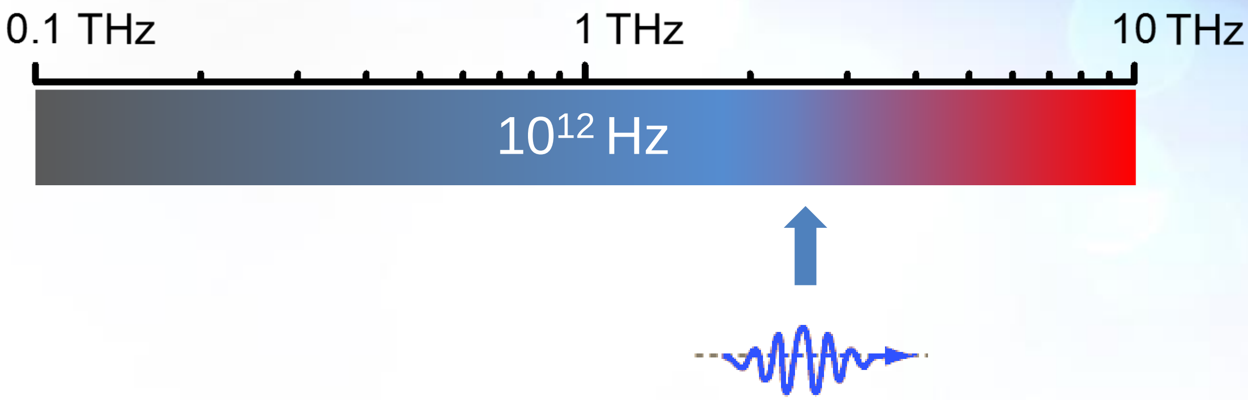
Fully integrated for material properties:
- Electronic
- Magnetic
- Chemical

Electronic thin films
Organic Electronics
Spintronics

Lake Shore CRYOTRONICS

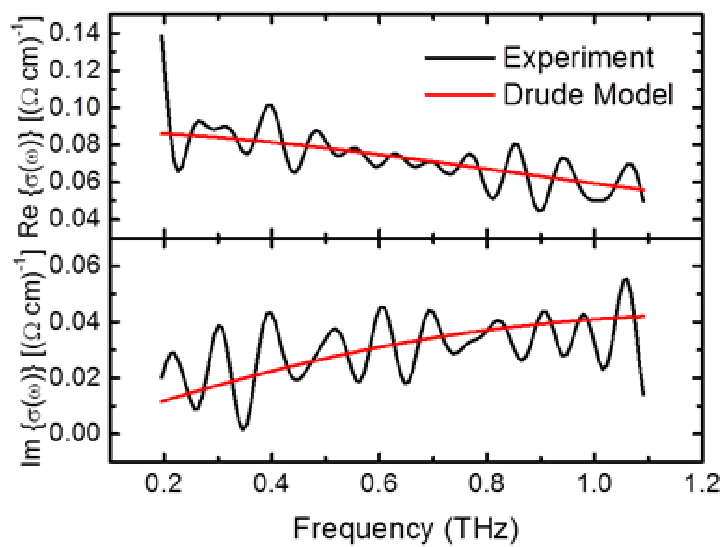
Why THz?

Equivalent Scales for THz



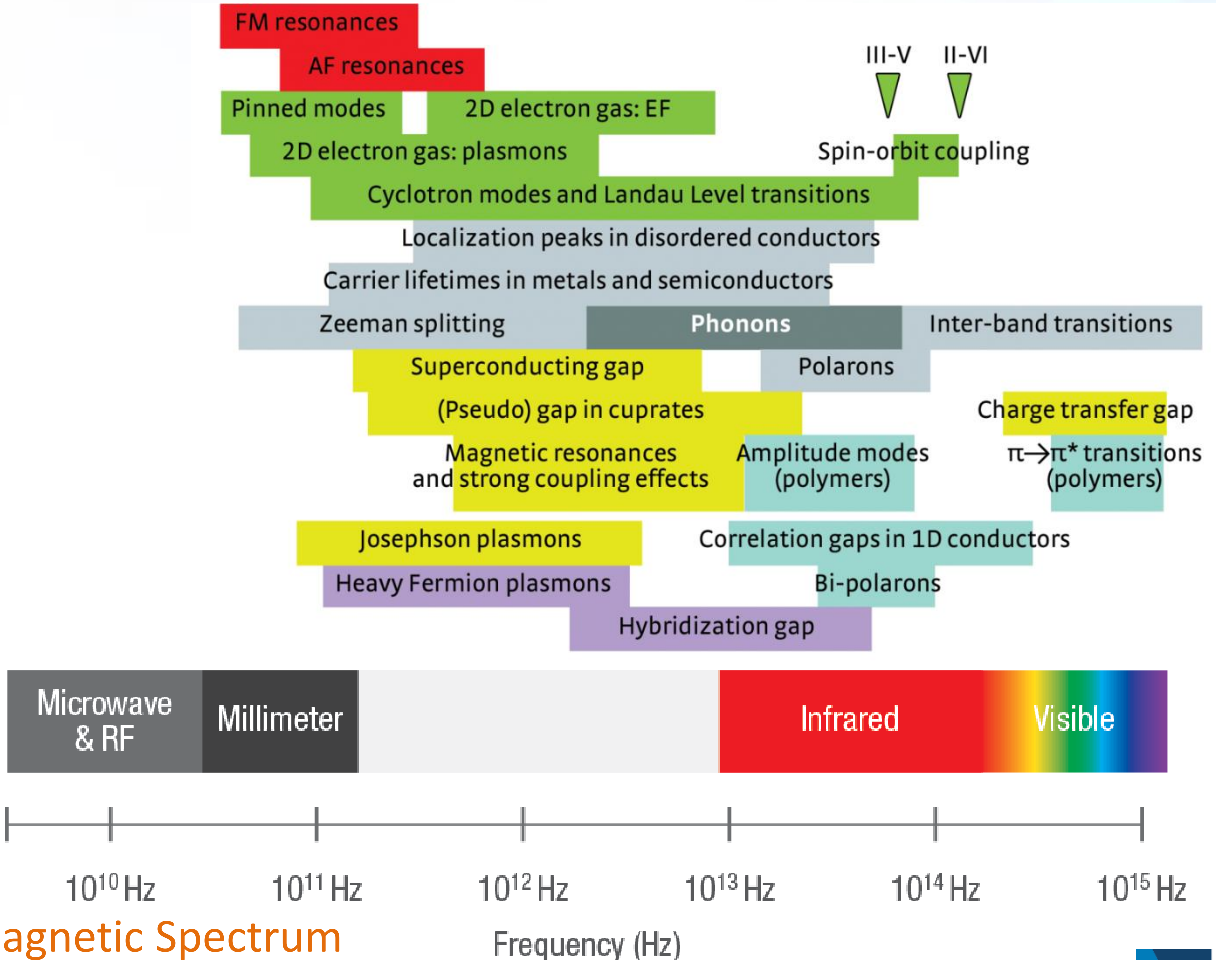
2.5 THz ~ 10 meV

- Alignment of THz energy levels with phenomena of interest
  - Vibrational Resonances
  - Novel Spin Resonances
  - Free Carrier motion in semiconductors



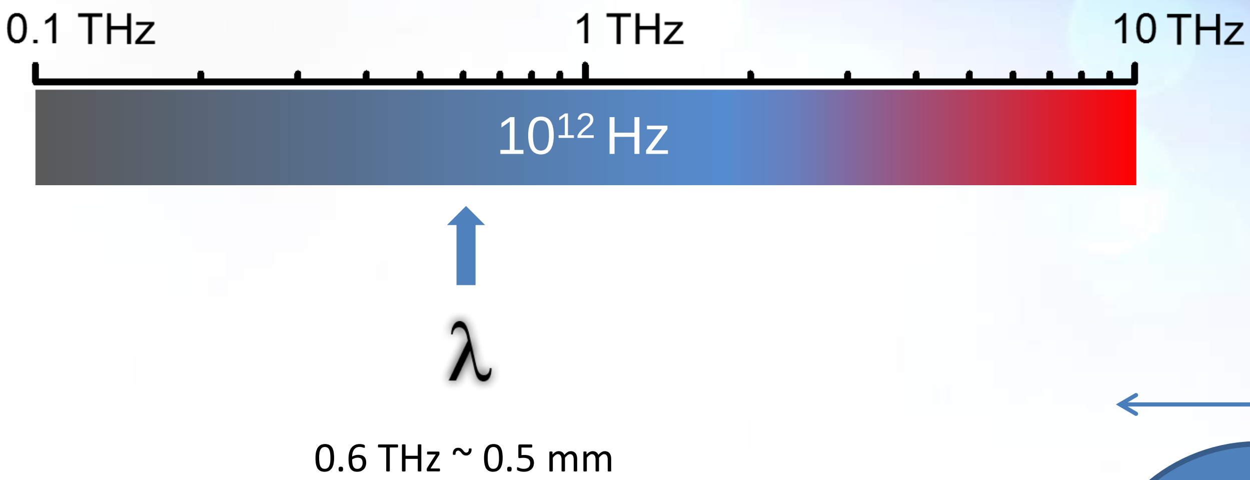
Materials Phenomena

D. N. Basov, et al.
"*Electrodynamics of correlated electron materials*"
Rev. Mod. Phys. 85(2), 471 (2011).

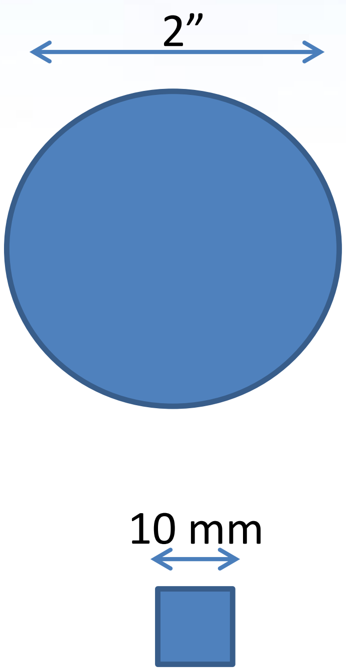


The Electromagnetic Spectrum

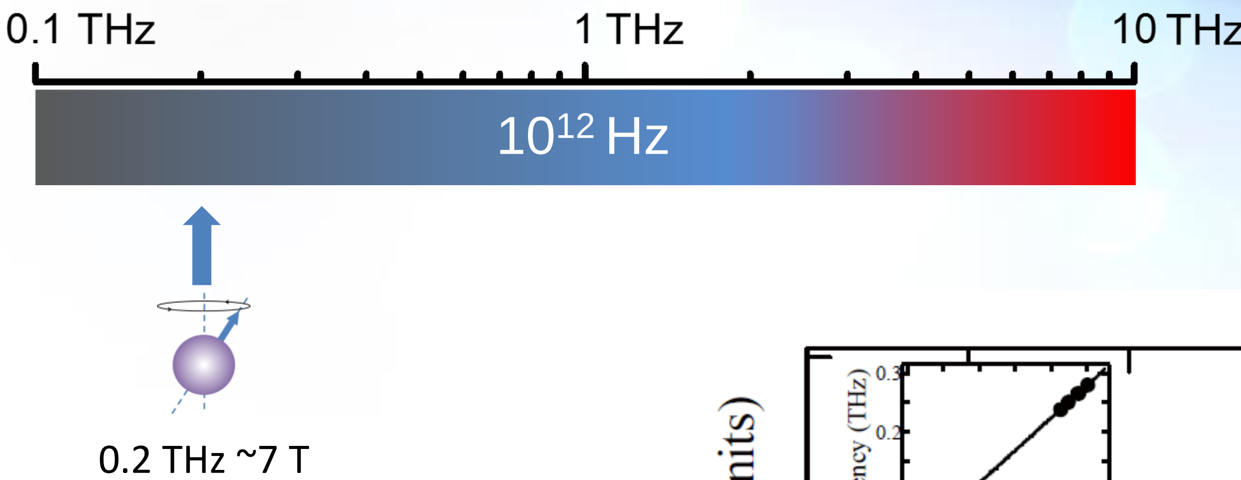
Equivalent Scales for THz



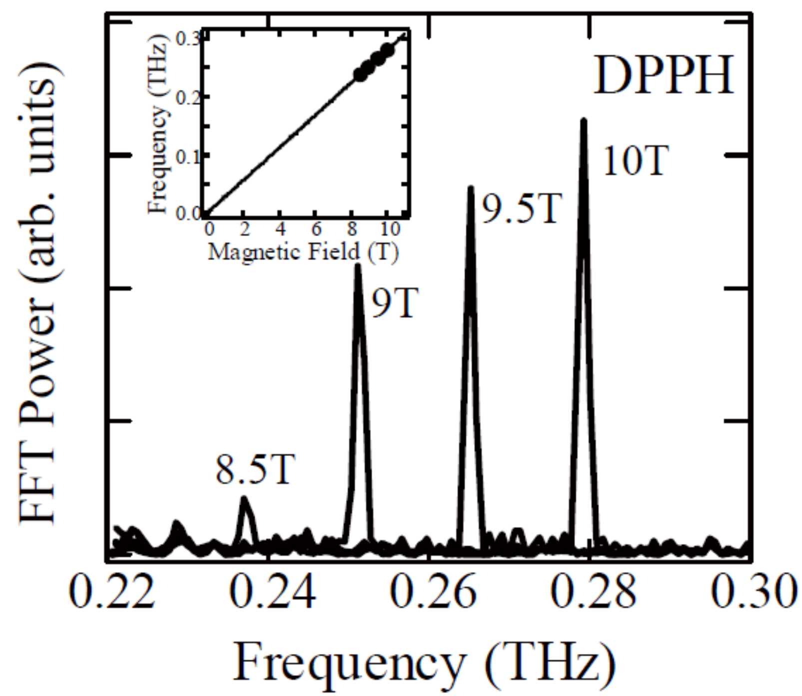
- THz wavelengths match the feature sizes of development-grade electronic materials
  - Non-contact electronic characterization
  - Novel magnetic materials



Equivalent Scales for THz

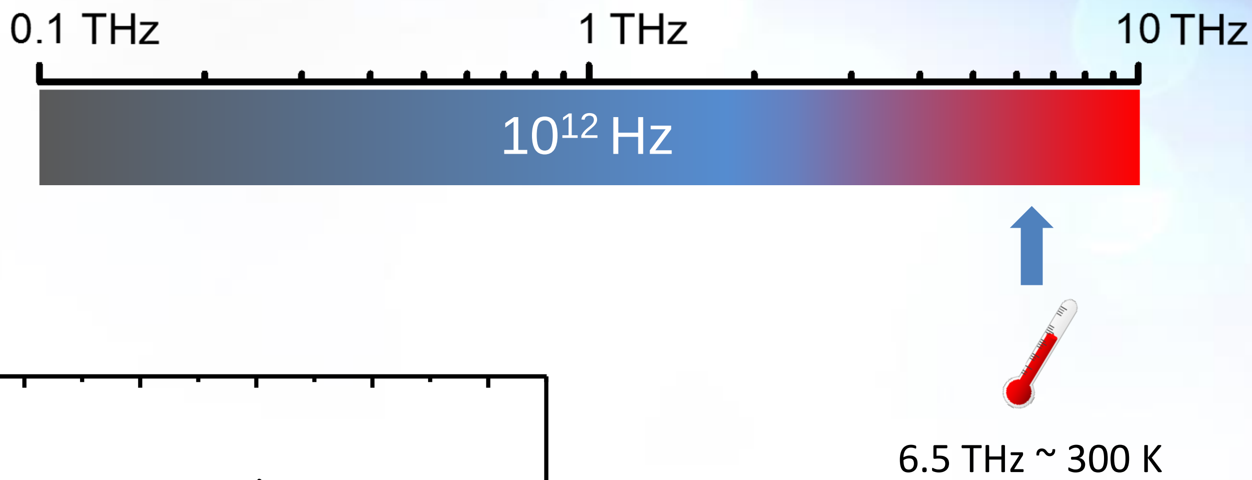


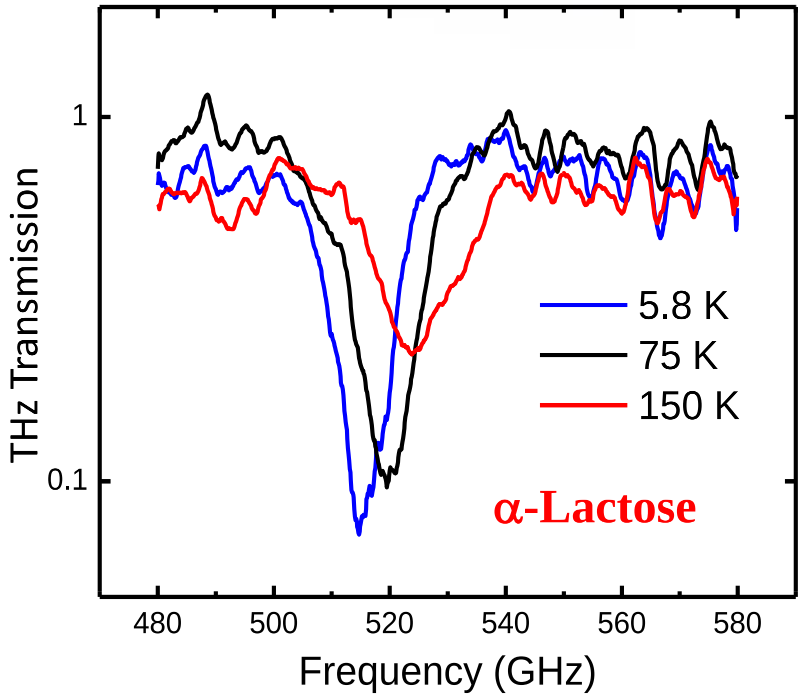
- Coupling to spin-based materials at THz frequencies
  - High speed computing paradigms
  - May require large fields



Nagashima, T.; Nishitani, J.; Kozuki, Kohei, "*Lasers & Electro Optics & The Pacific Rim Conference on Lasers and Electro-Optics, 2009. CLEO/PACIFIC RIM '09. Conference on* , vol., no., pp.1,2, 30-3 Aug. 2009

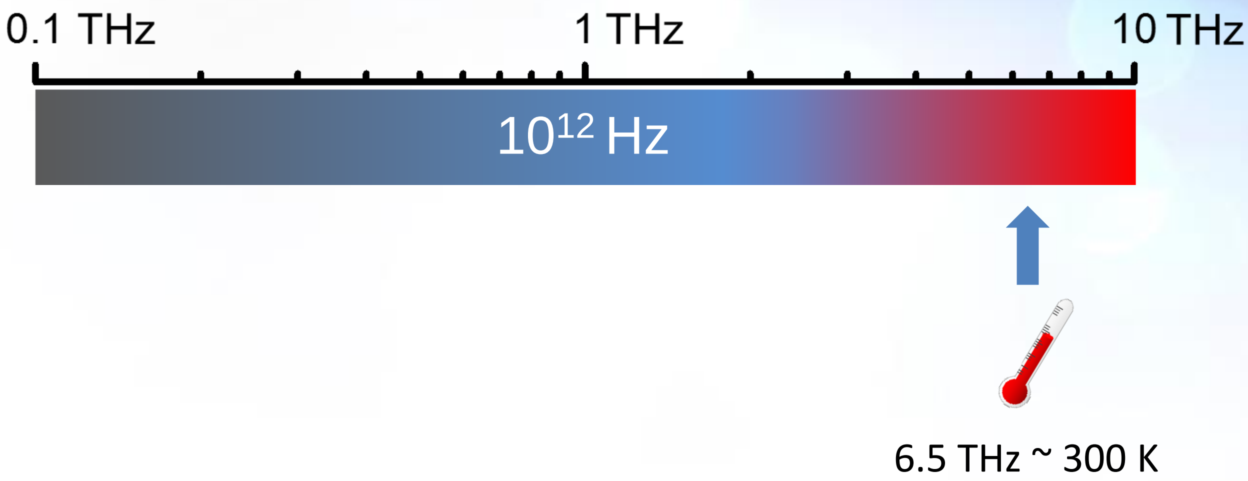
Equivalent Scales for THz





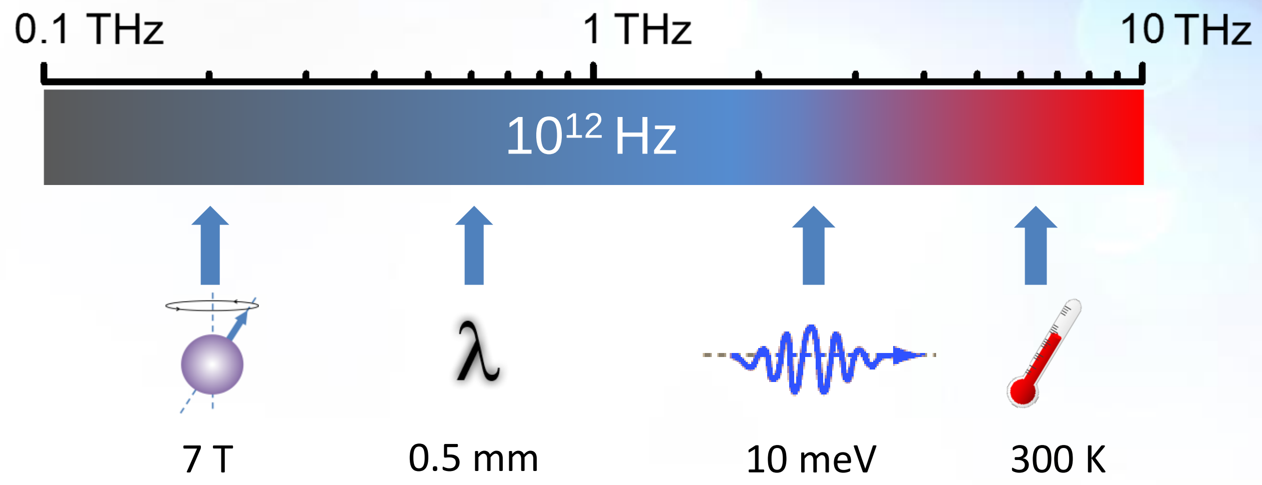
- Cryogenic temperatures
  - Homogeneous broadening of vibrational resonances

Equivalent Scales for THz



- Cryogenic temperatures
  - Homogeneous broadening of vibrational resonances
  - Temperature dependent carrier concentration and mobility

Equivalent Scales for THz

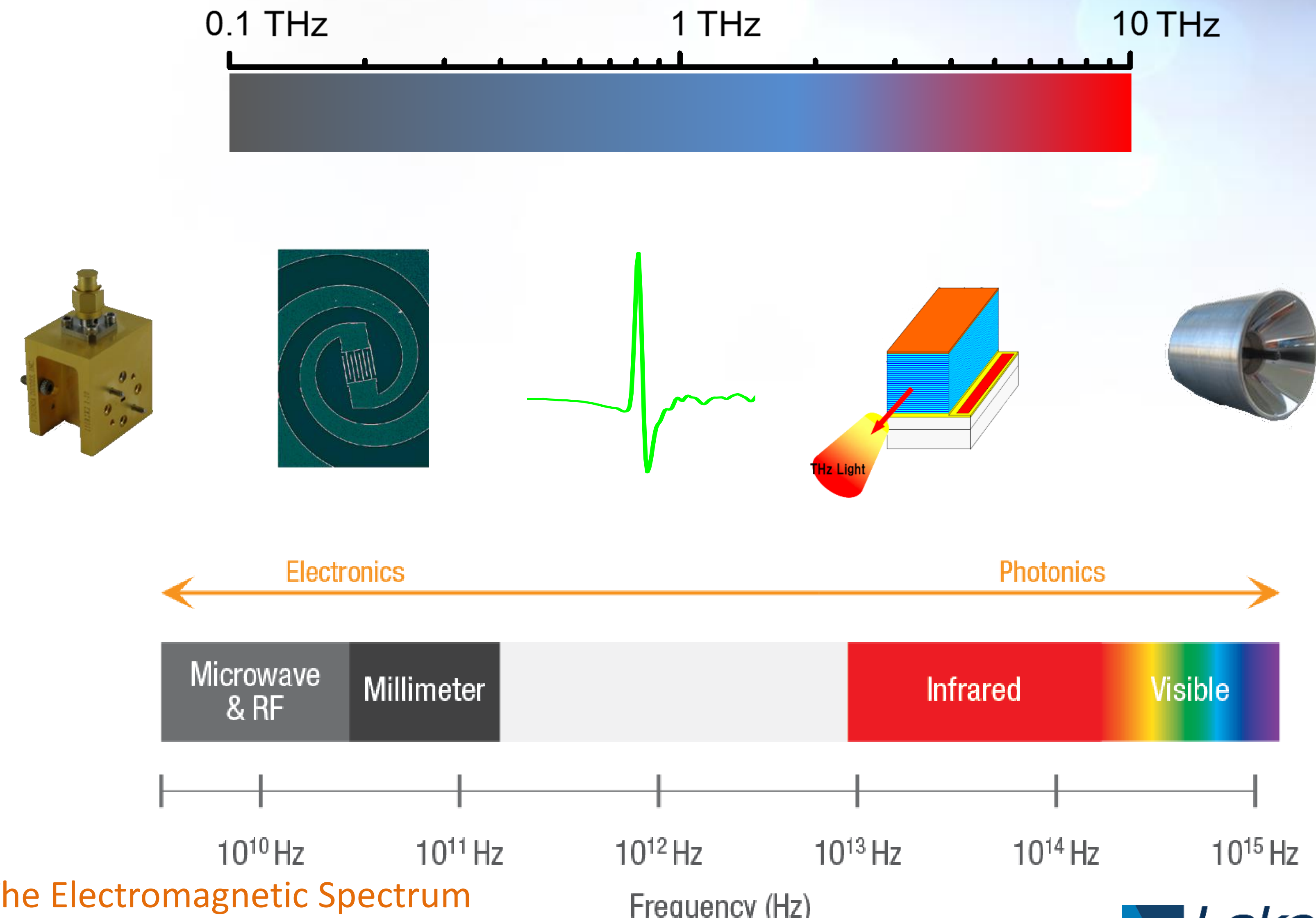


- Alignment of THz energy levels with phenomena of interest
- THz wavelengths match the feature sizes of development-grade electronic materials
- Coupling to spin-based materials at THz frequencies
- Cryogenic temperatures

THz System Product Challenges

- THz performance suitable for materials characterization
  - Continuous tuning over bandwidth
  - Spectral resolution
- Ability to characterize samples while exposed to variable cryogenic temperatures and magnetic fields
- Affordable THz-based measurement platform
- Robust Design
- Proceduralized experimental methods and reliable analysis of the spectral results
  - Convenient sample insertion without complicated alignment
  - Enable materials developers to rapidly begin productive research

Filling the THz Gap



The Electromagnetic Spectrum

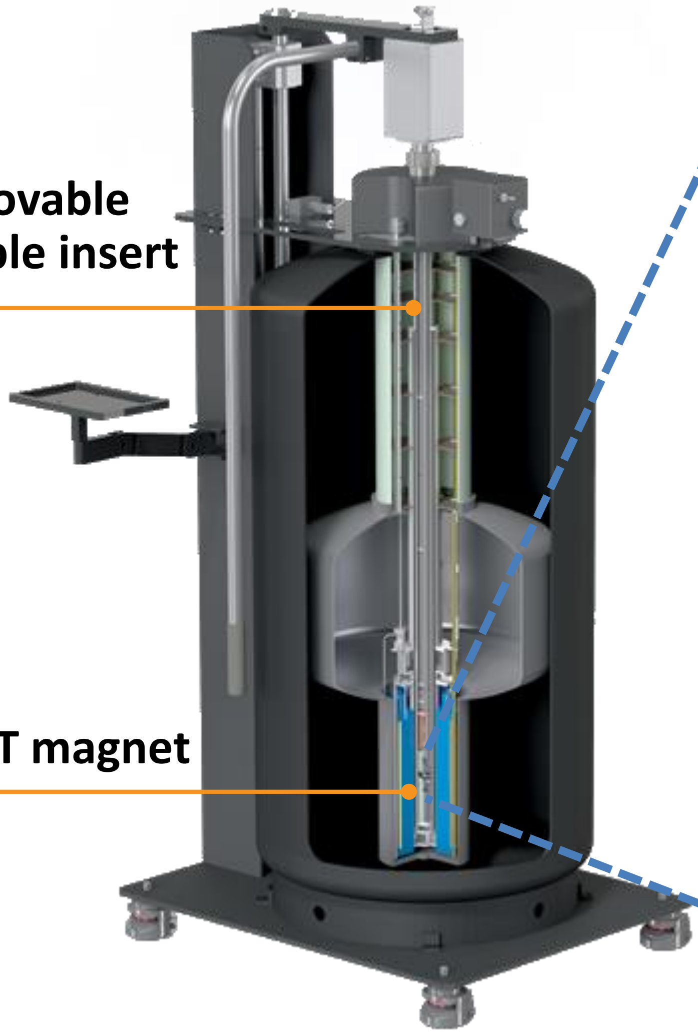
THz with cryogenics & magnetics

- Many materials of interest for THz require variable temperature and/or high magnetic fields
- Optical cryostats are the standard approach
  - THz generation outside the environment
  - Must pass optical energy through windows, cutting signal power and spectral distortion
- **Not ideal for THz spectroscopies**

Variable Temperature and High Magnetic Field THz Platform

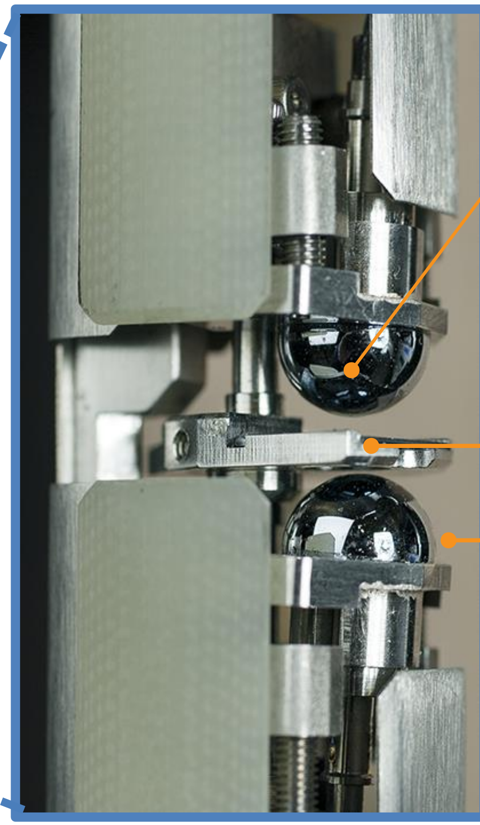
Cryostat

Removable sample insert



±9 T magnet

Sample Space



Cryo-compatible THz emitter with collimating optics

Rotatable sample stage (10 mm × 10 mm)

Thermally stable optical alignment stages

Lake Shore CRYOTRONICS

Integrated THz System Details

Application software for turnkey operation

- Experiment setup/run
- Analysis of spectral data
- Calculation of material properties

Fiber-based optical platform for CW THz spectroscopy

- CW THz spectrometer instrument
- Amplitude and phase detection from 200 GHz to 1.5 THz
- Spectral resolution under 500 MHz
- Circularly polarized light

Integrated controls

- Model 336 cryogenic temperature controller
- Model 625 superconducting magnet power supply

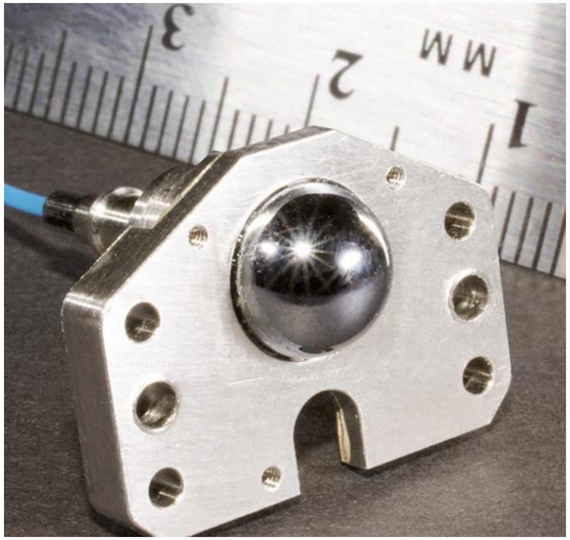
Integrated cryostat & insert

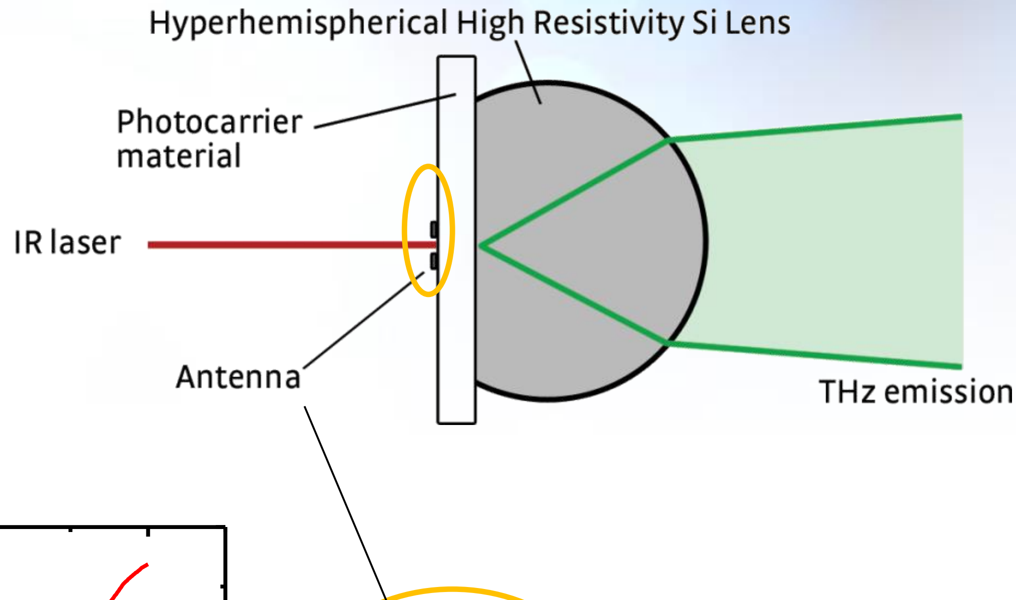
- Variable temperatures from 5 K to 300 K
- Sample size – 10 mm
- Measurement – THz transmission

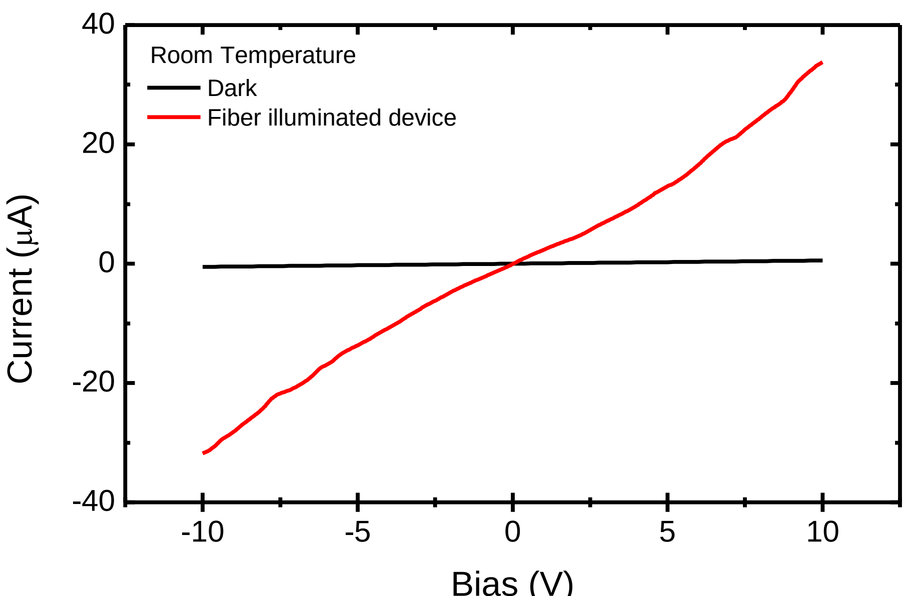
Superconducting magnet

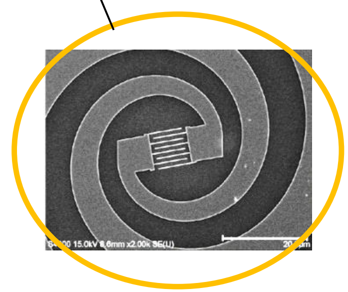
- High magnetic fields to ±9 Tesla

Photoconductive THz Emitter



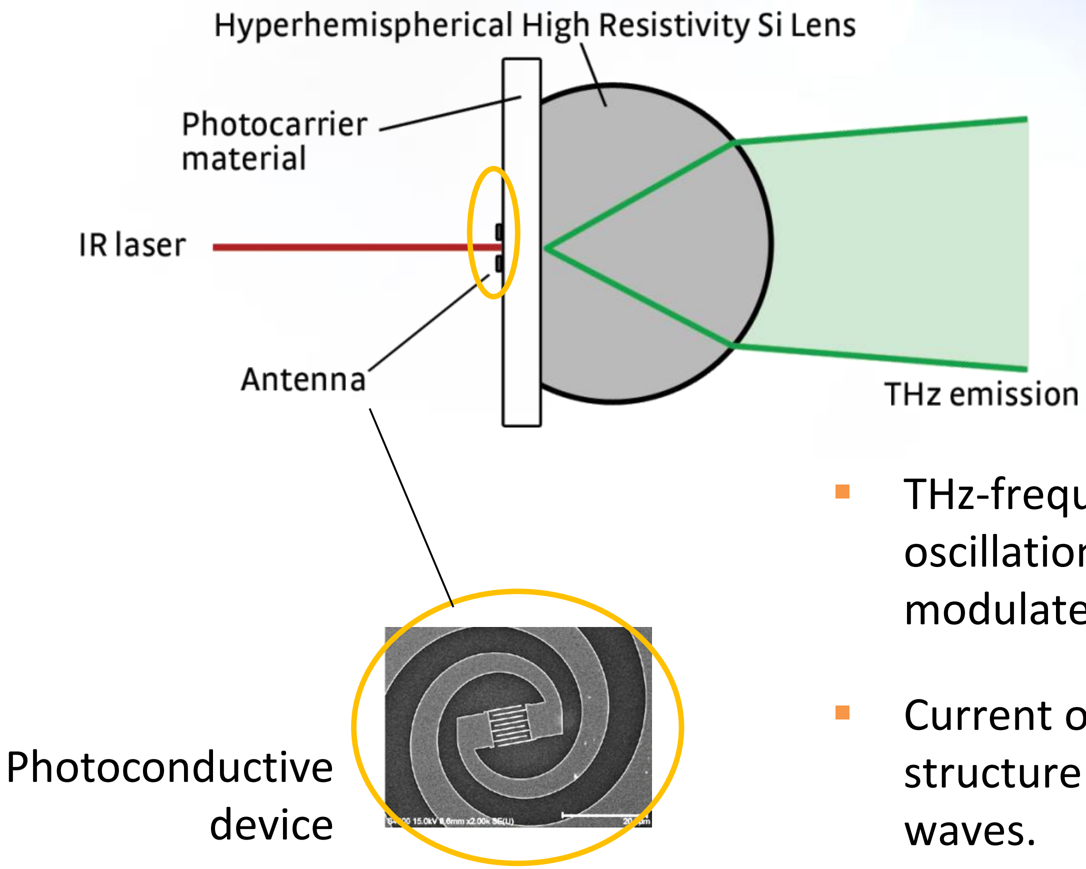






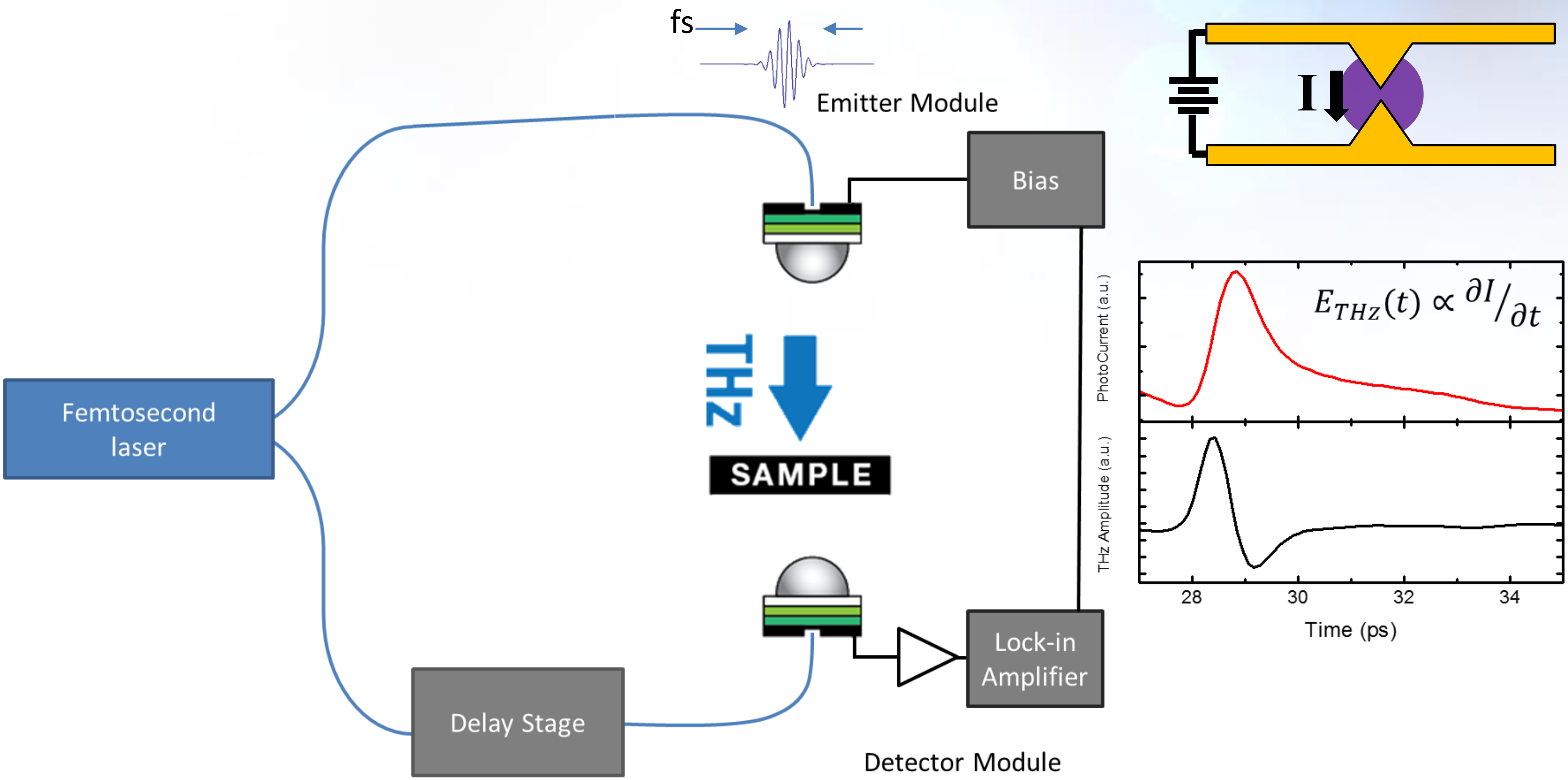
Photoconductive device

Photoconductive THz Emitter

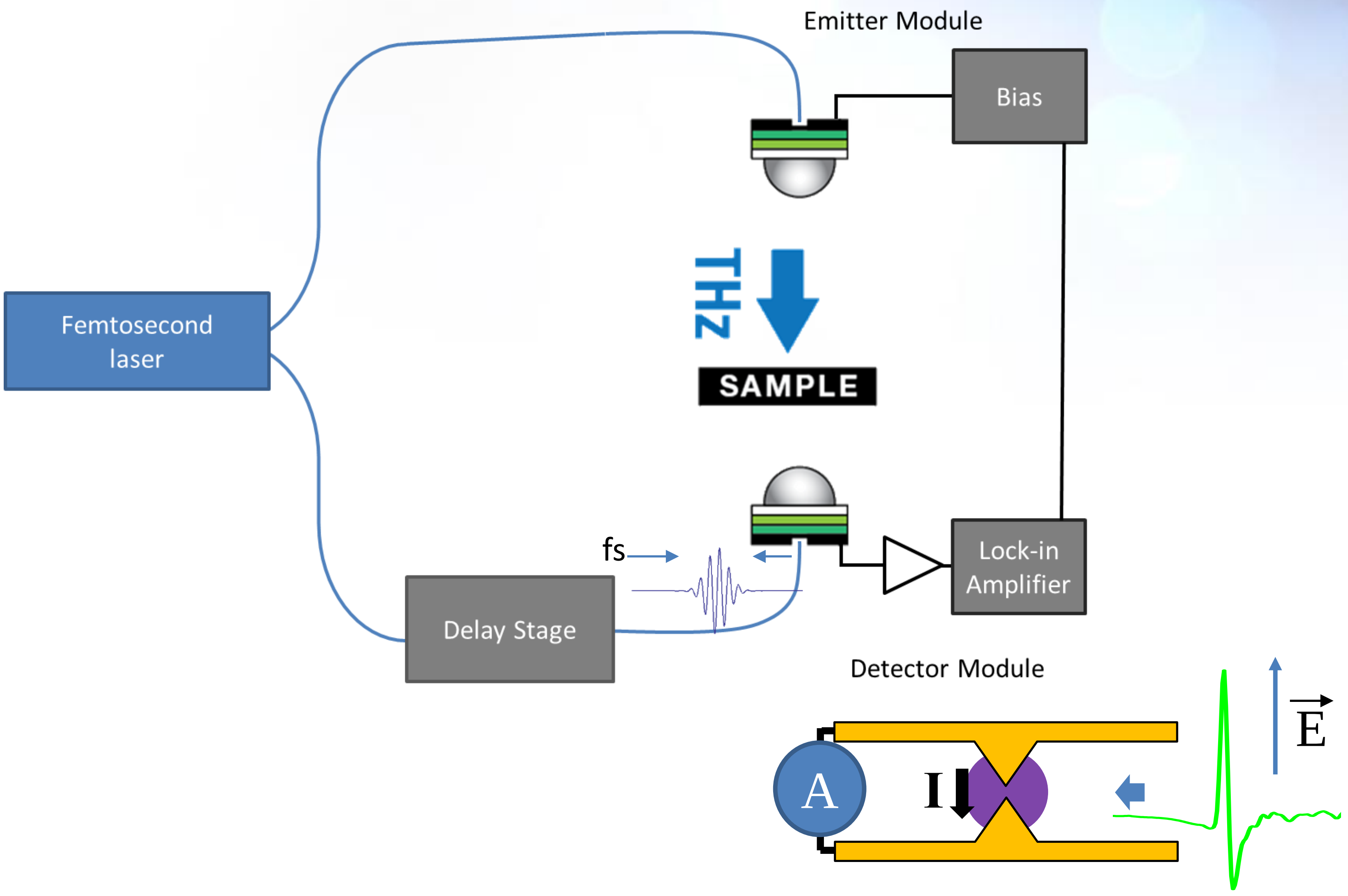


- THz-frequency transient current oscillations induced by amplitude modulated IR laser light
- Current oscillations in the antenna structure radiate propagating EM waves.
- A high resistivity Si lens is attached to the emitter device to couple the THz emission to free space.

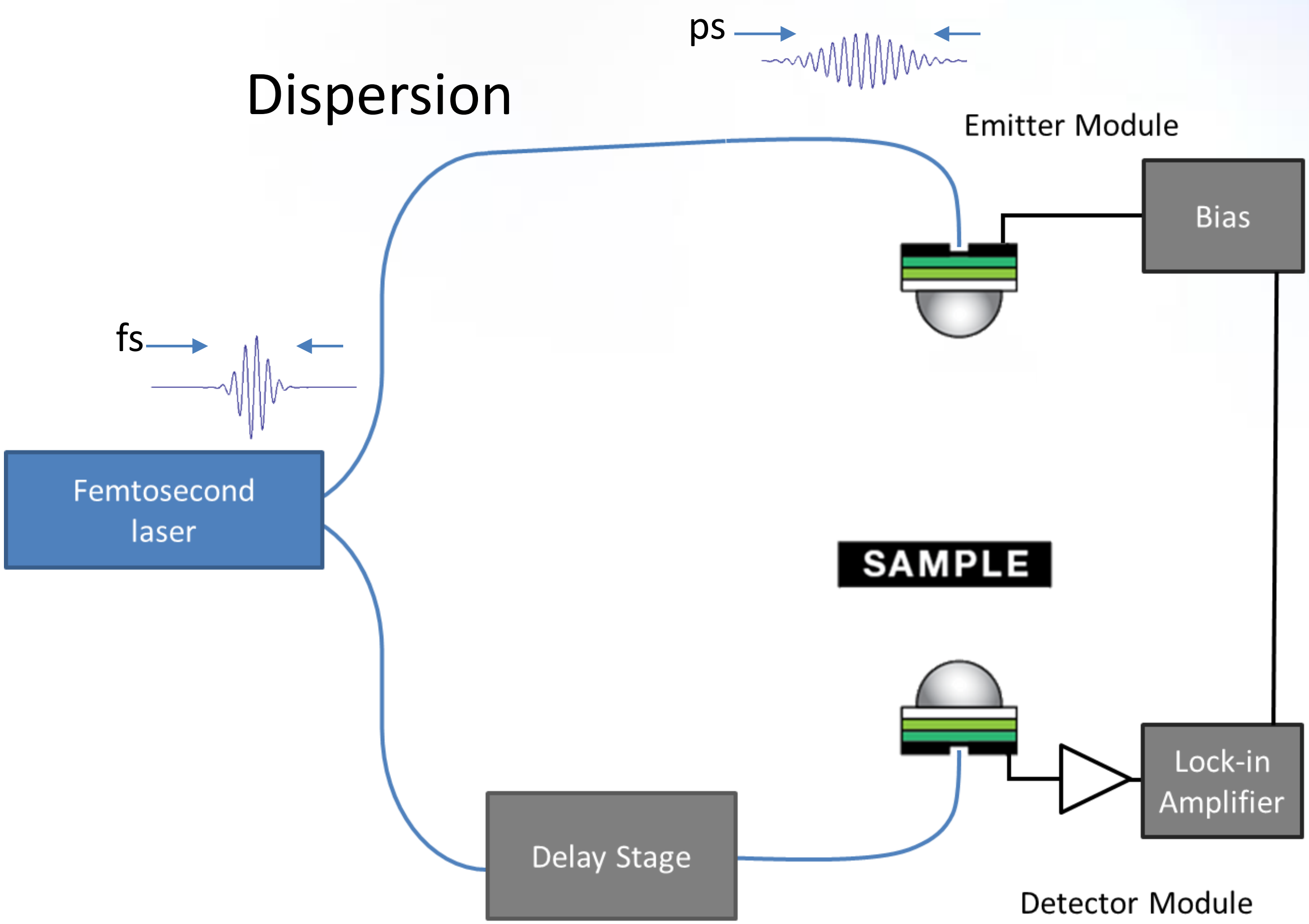
THz Time Domain Spectroscopy



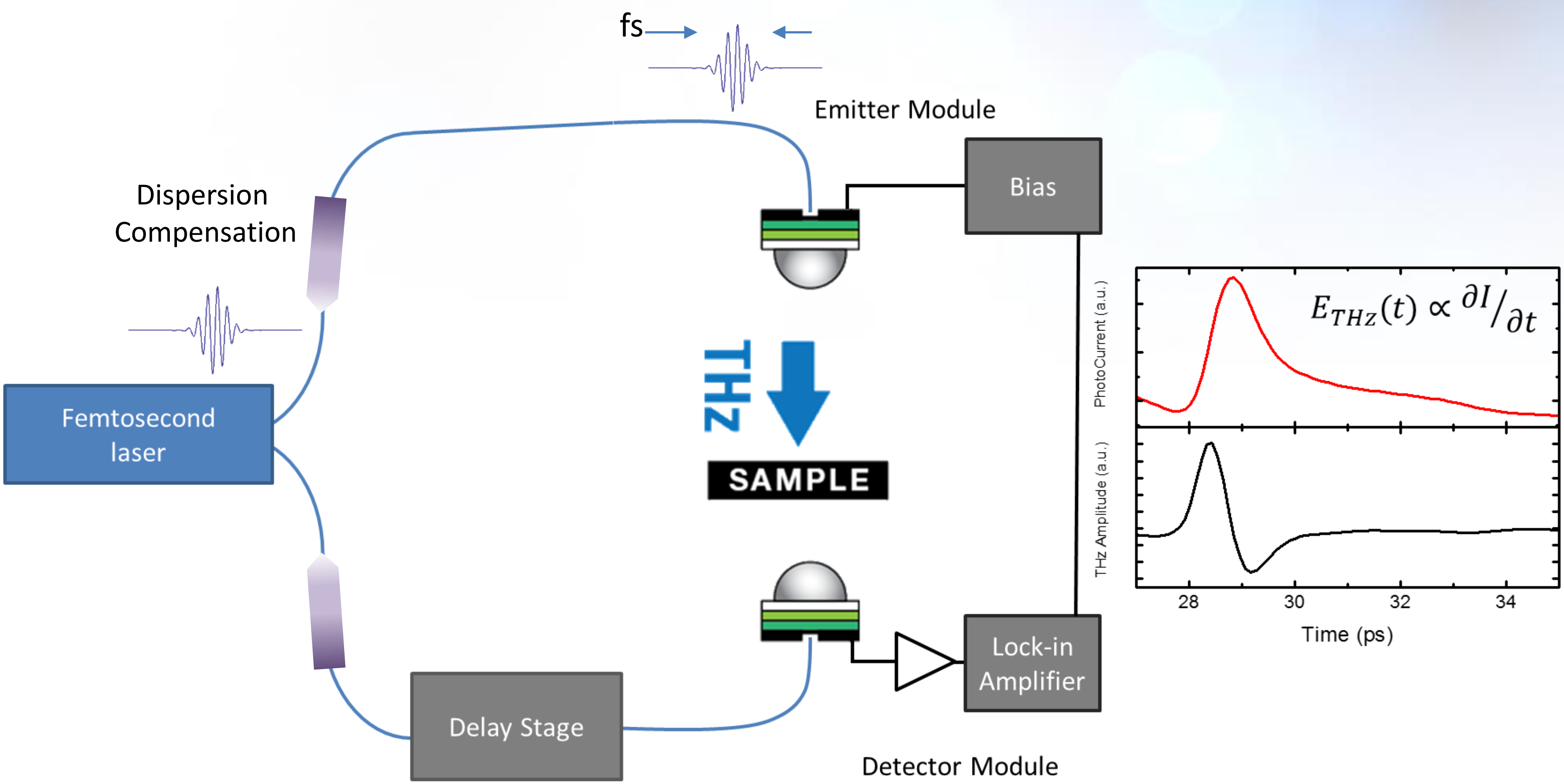
THz Time Domain Spectroscopy



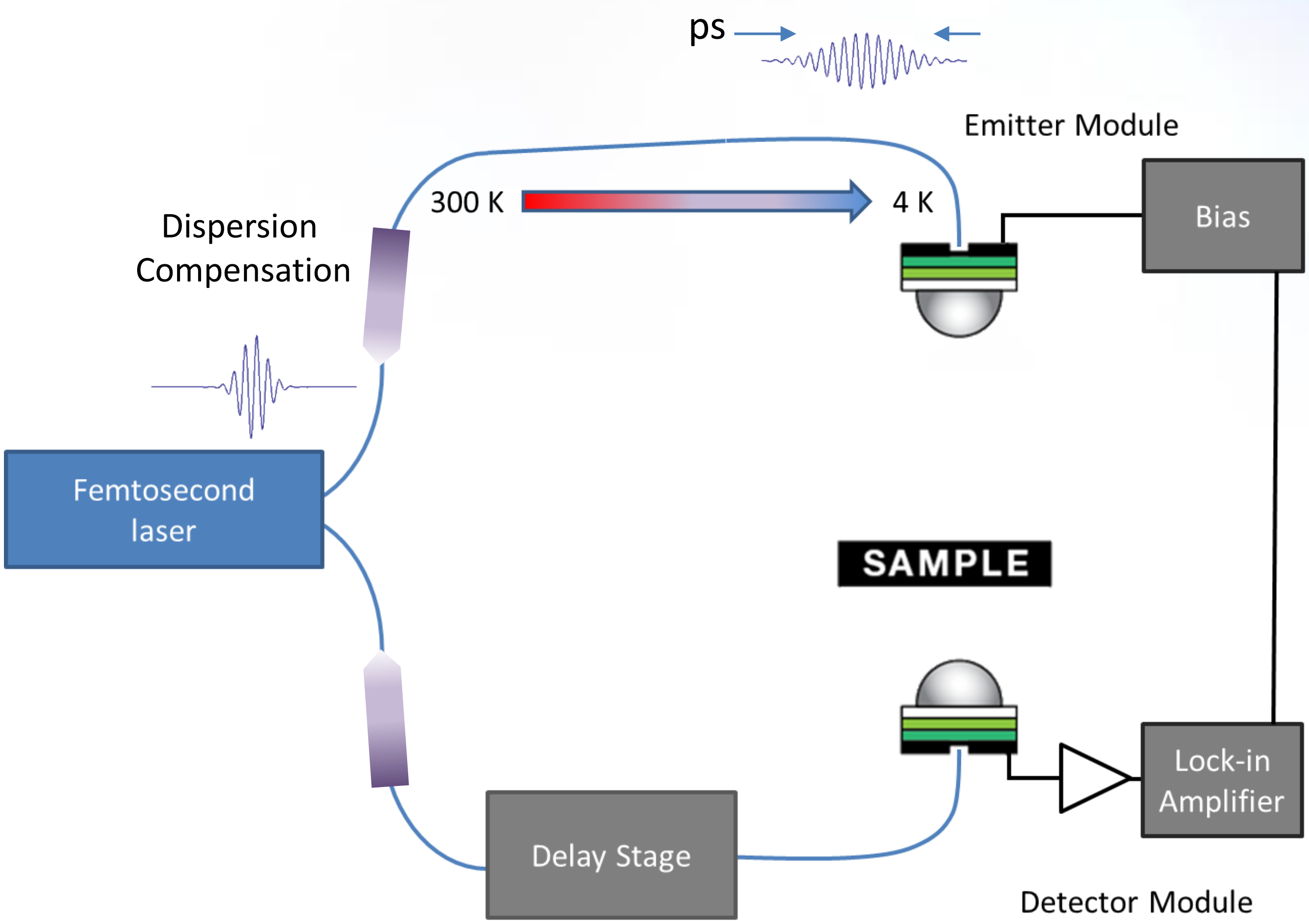
THz Time Domain Spectroscopy



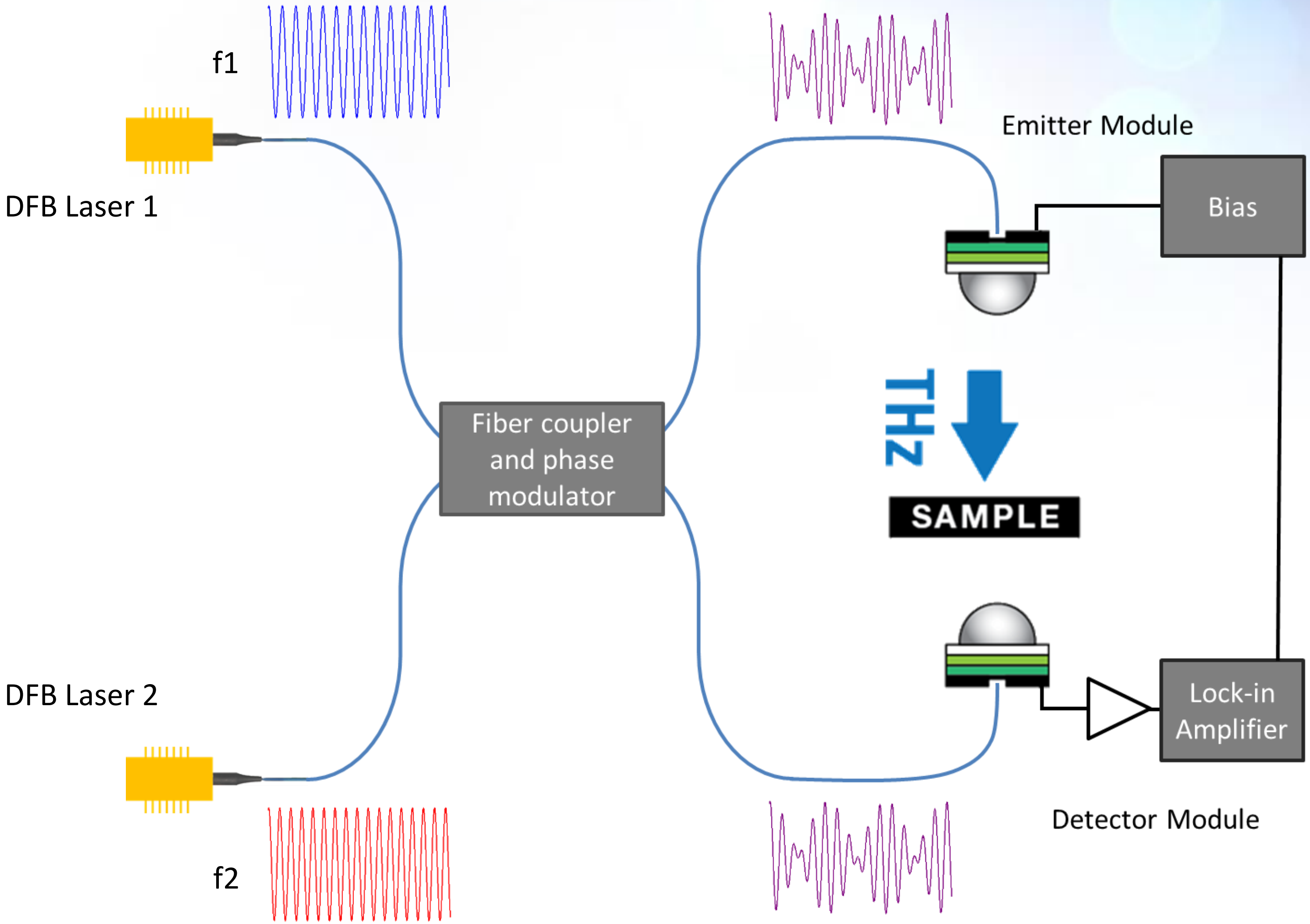
THz Time Domain Spectroscopy



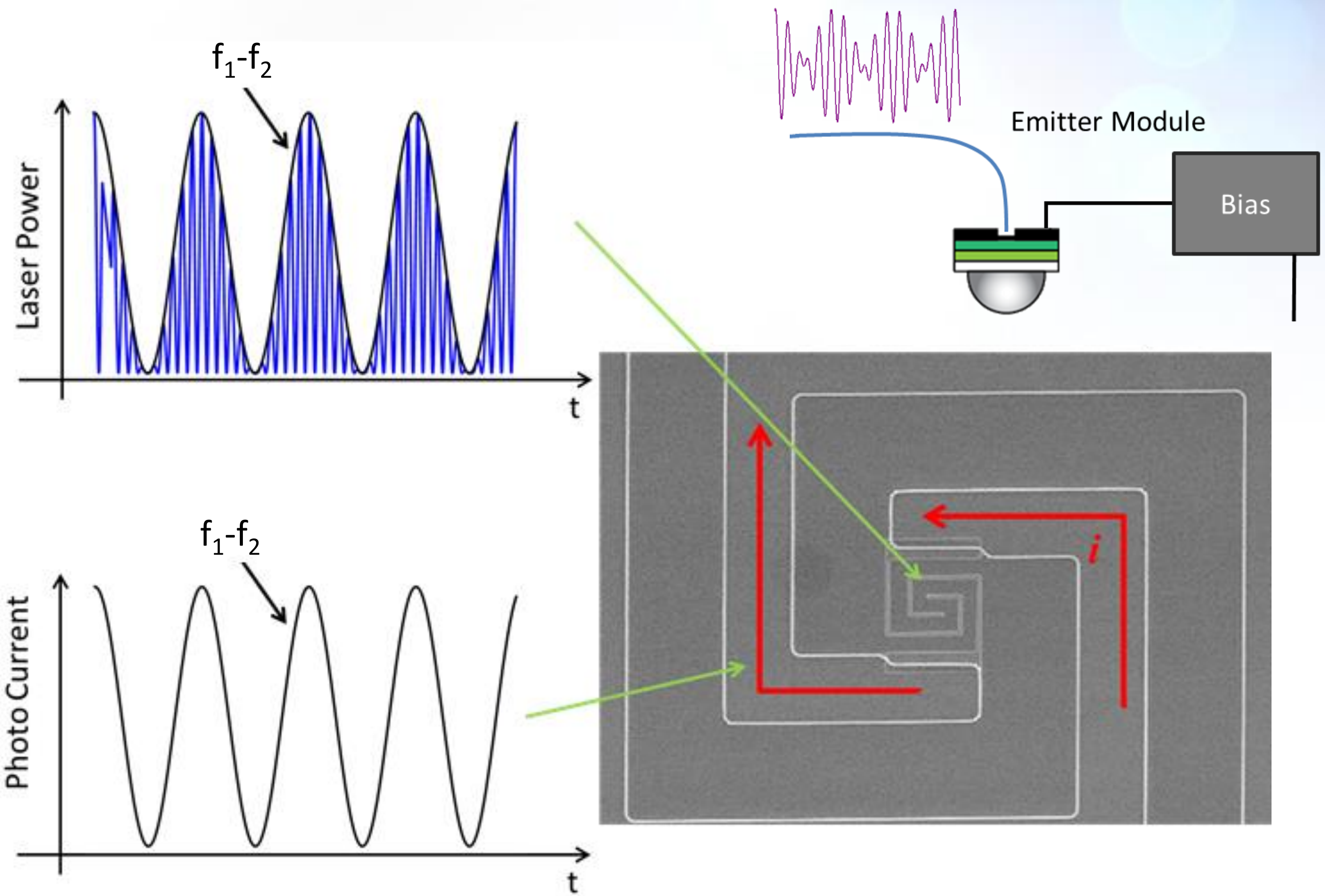
THz Time Domain Spectroscopy



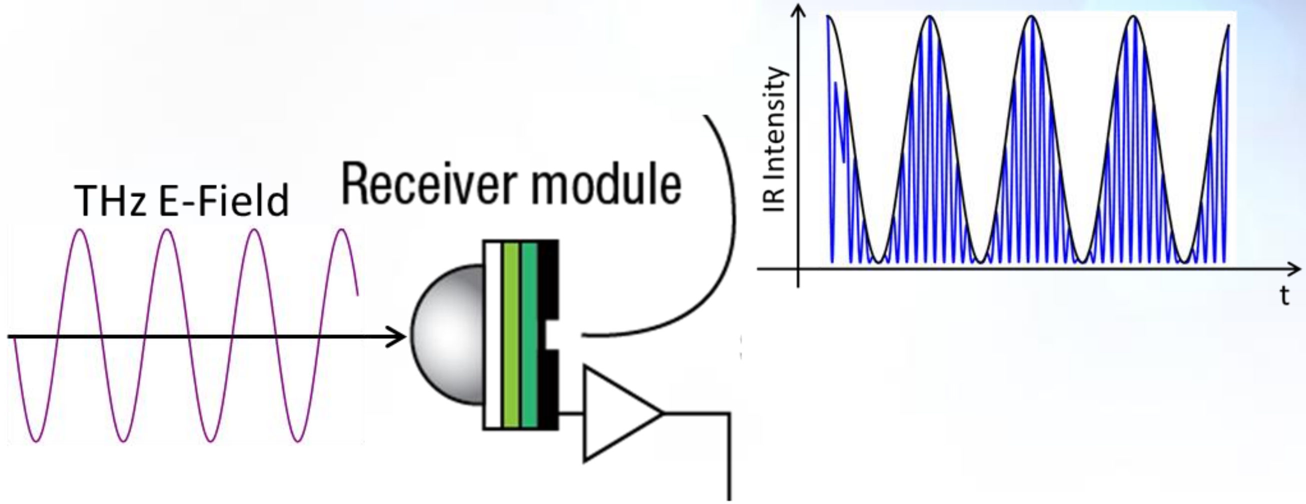
Continuous-Wave THz Spectroscopy

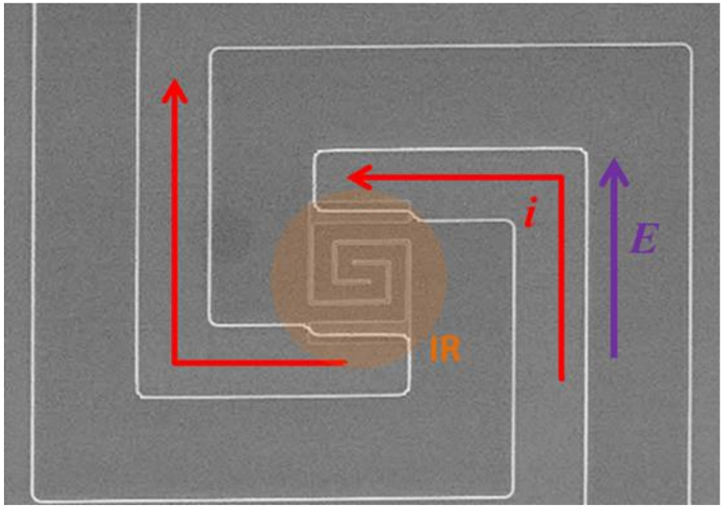


Continuous-Wave THz Spectroscopy - Generation

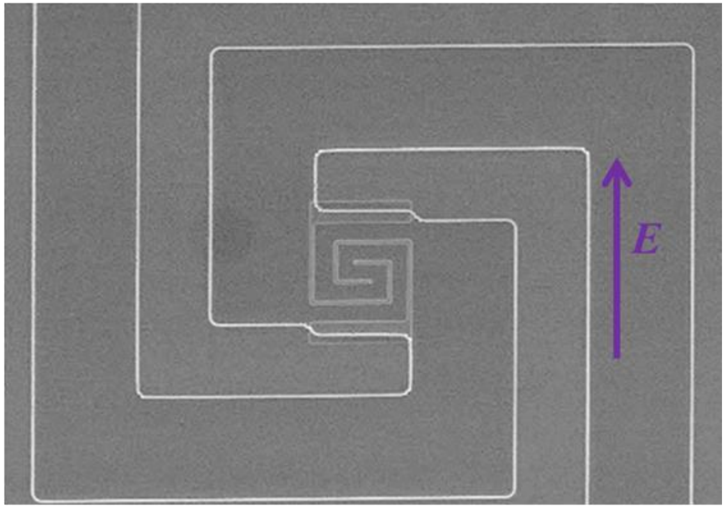


Continuous-Wave THz Spectroscopy - Detection





Detected current



No detected current

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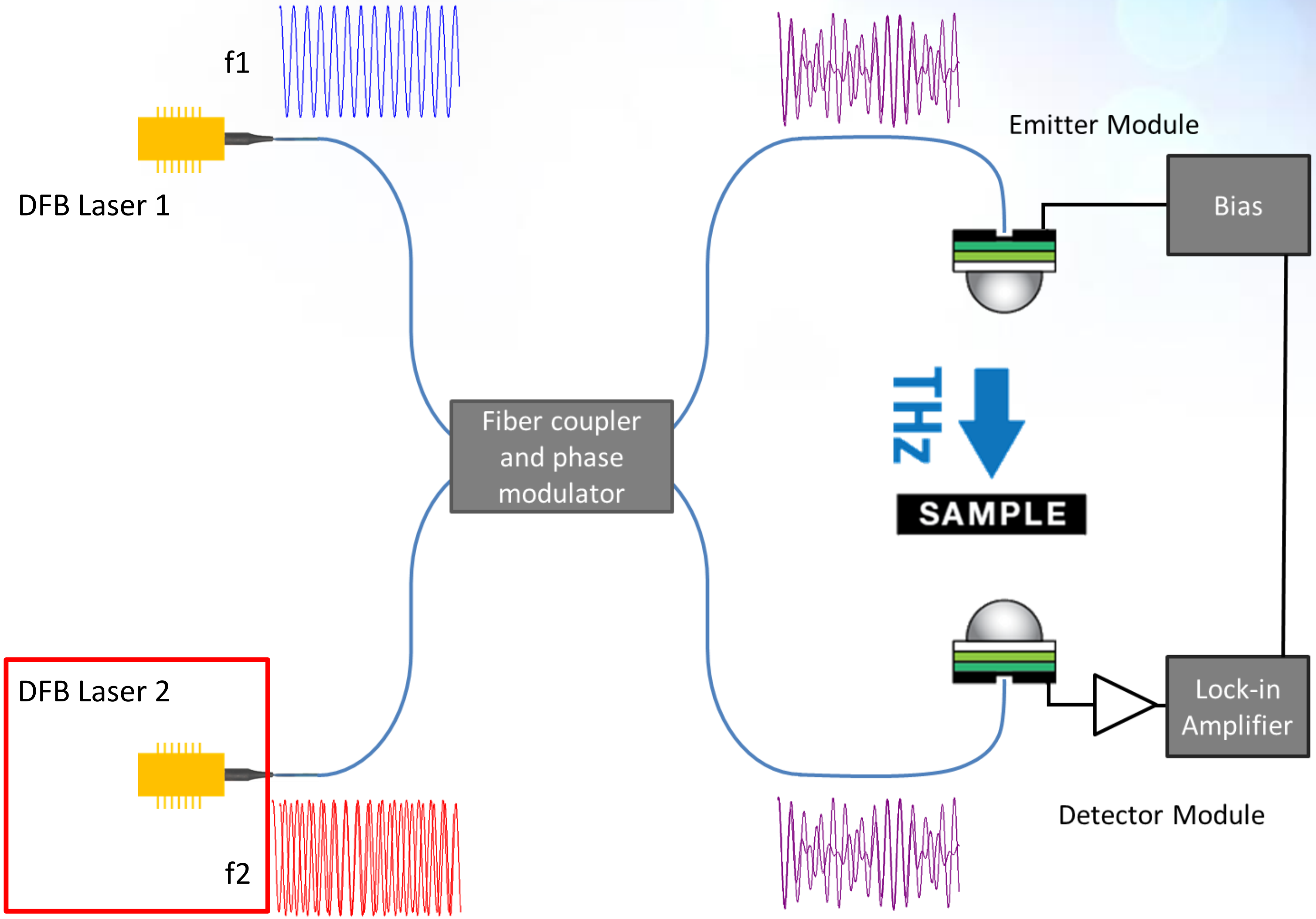
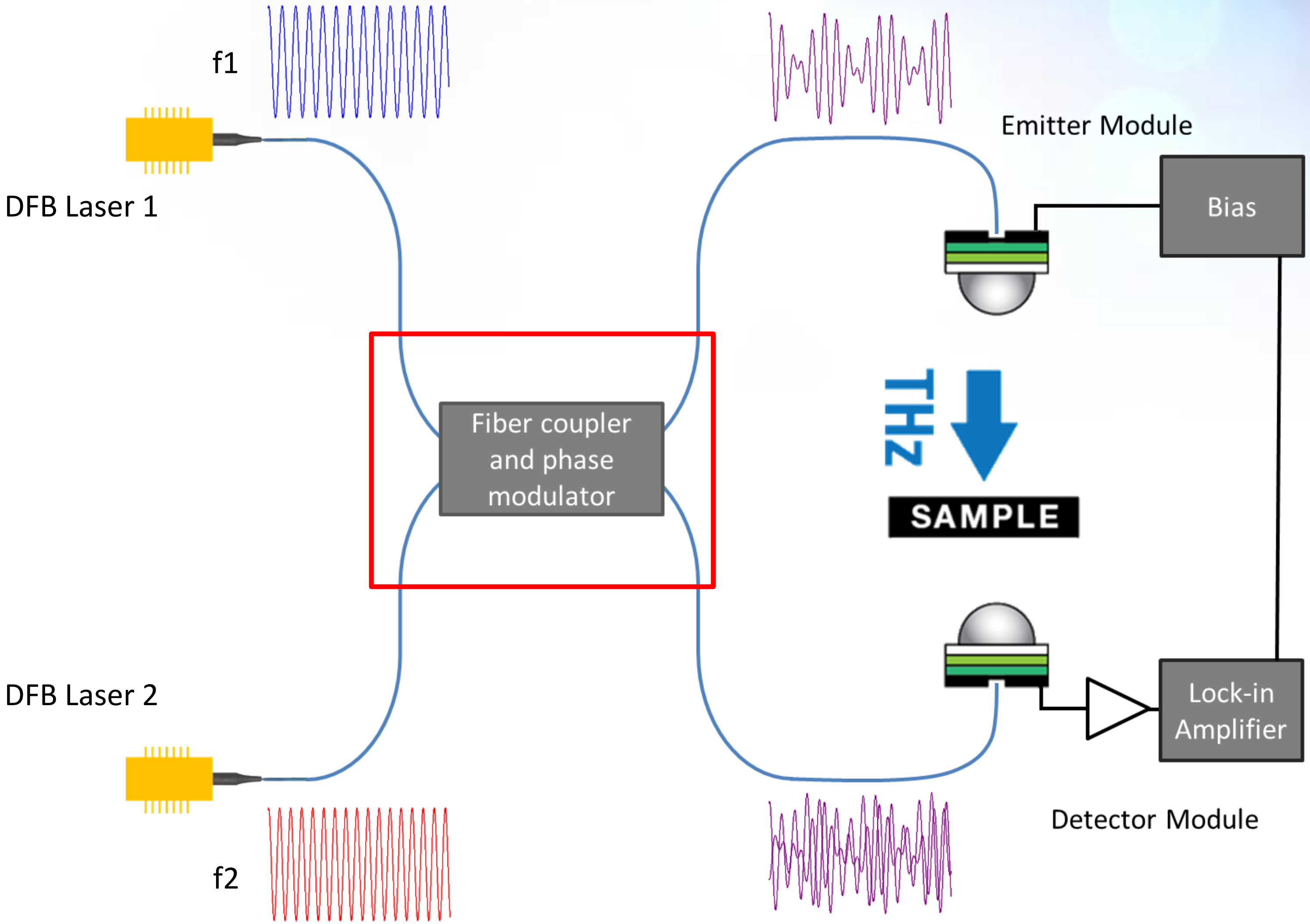
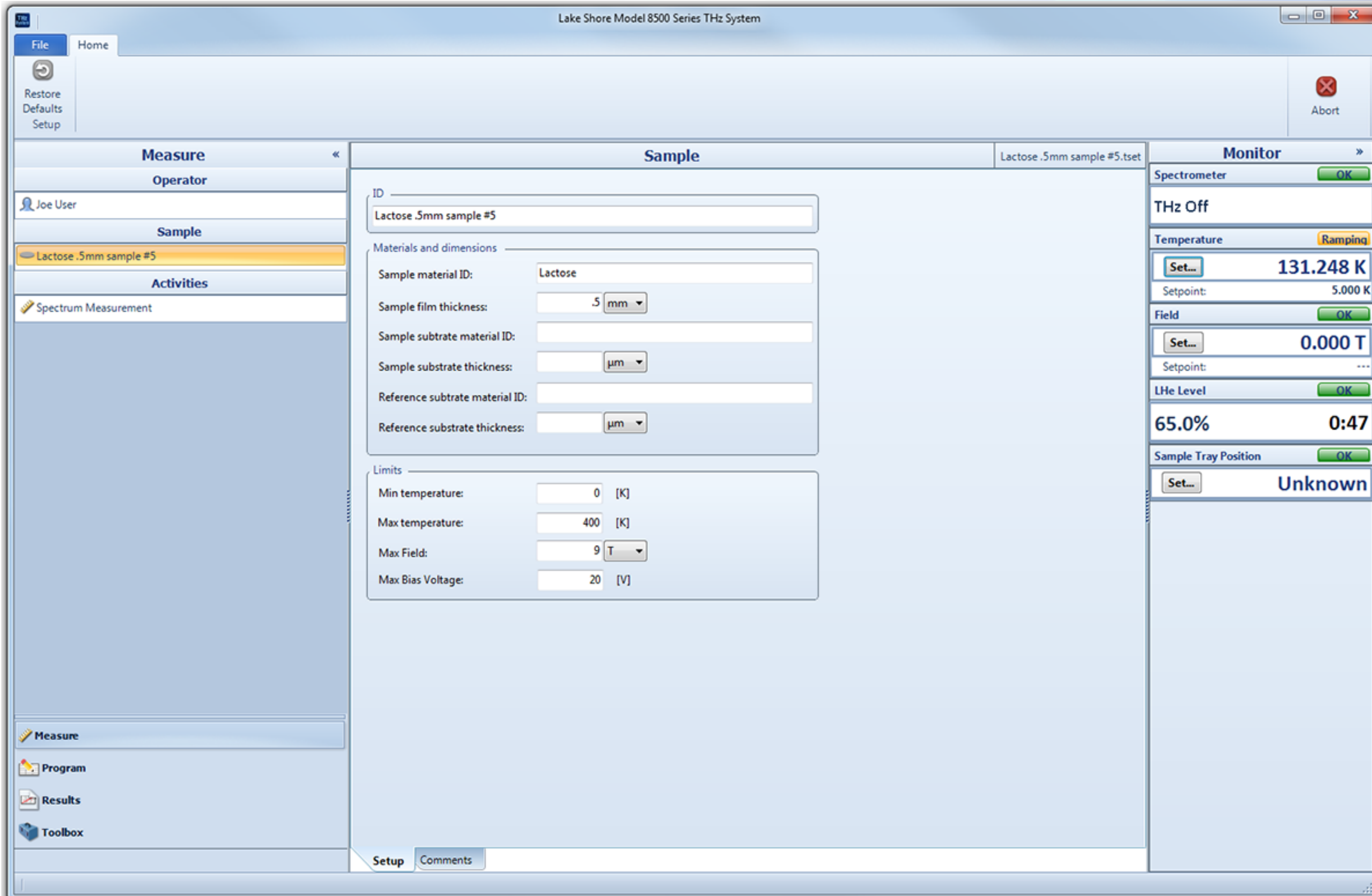
Continuous-Wave THz Spectroscopy - Frequency Tuning

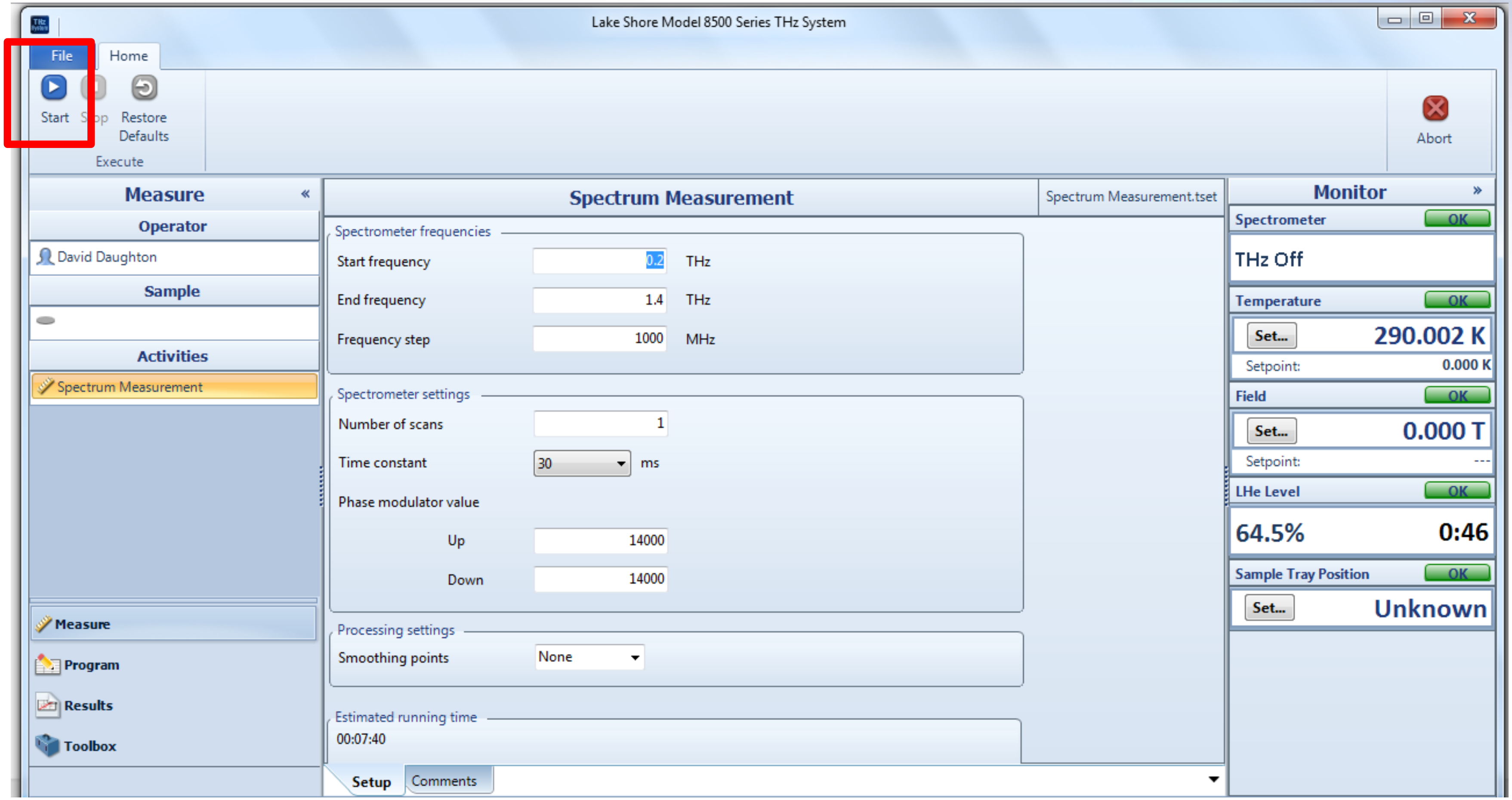



f1
DFB Laser 1
Emitter Module
Bias
Fiber coupler and phase modulator
THz
SAMPLE
DFB Laser 2
Lock-in Amplifier
Detector Module
f2

Integrated Software for Turn-key Operation

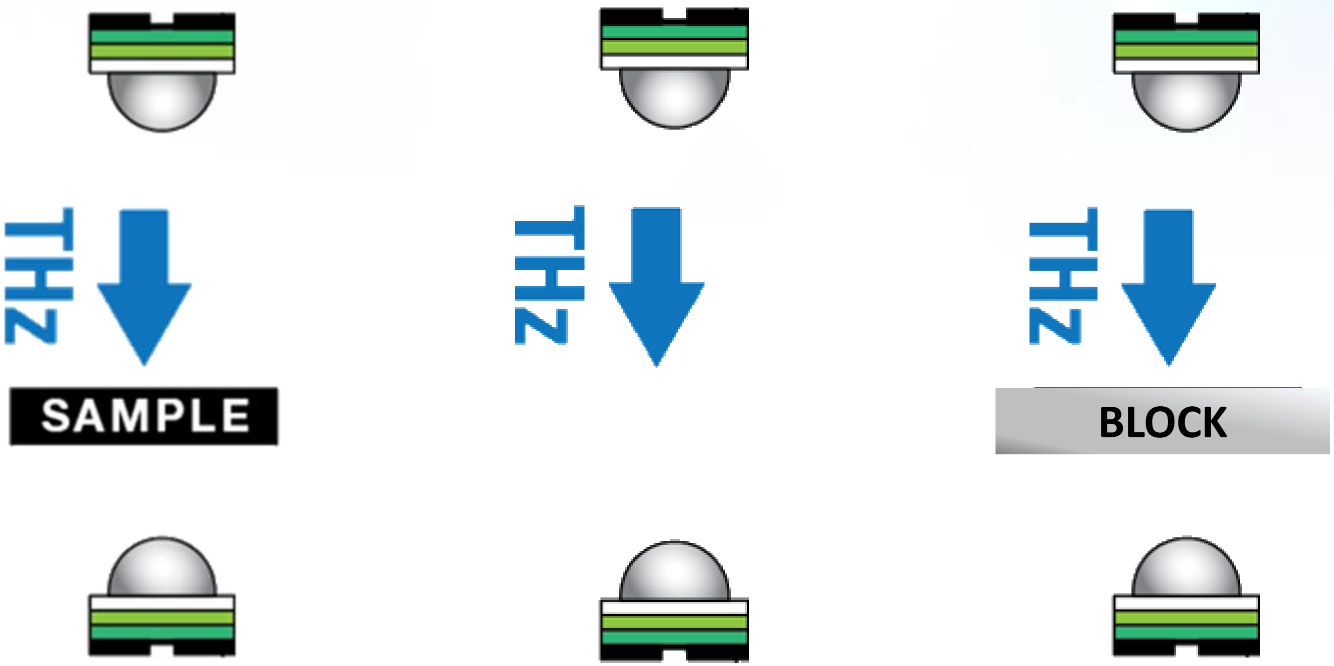


Integrated Software for Turn-key Operation

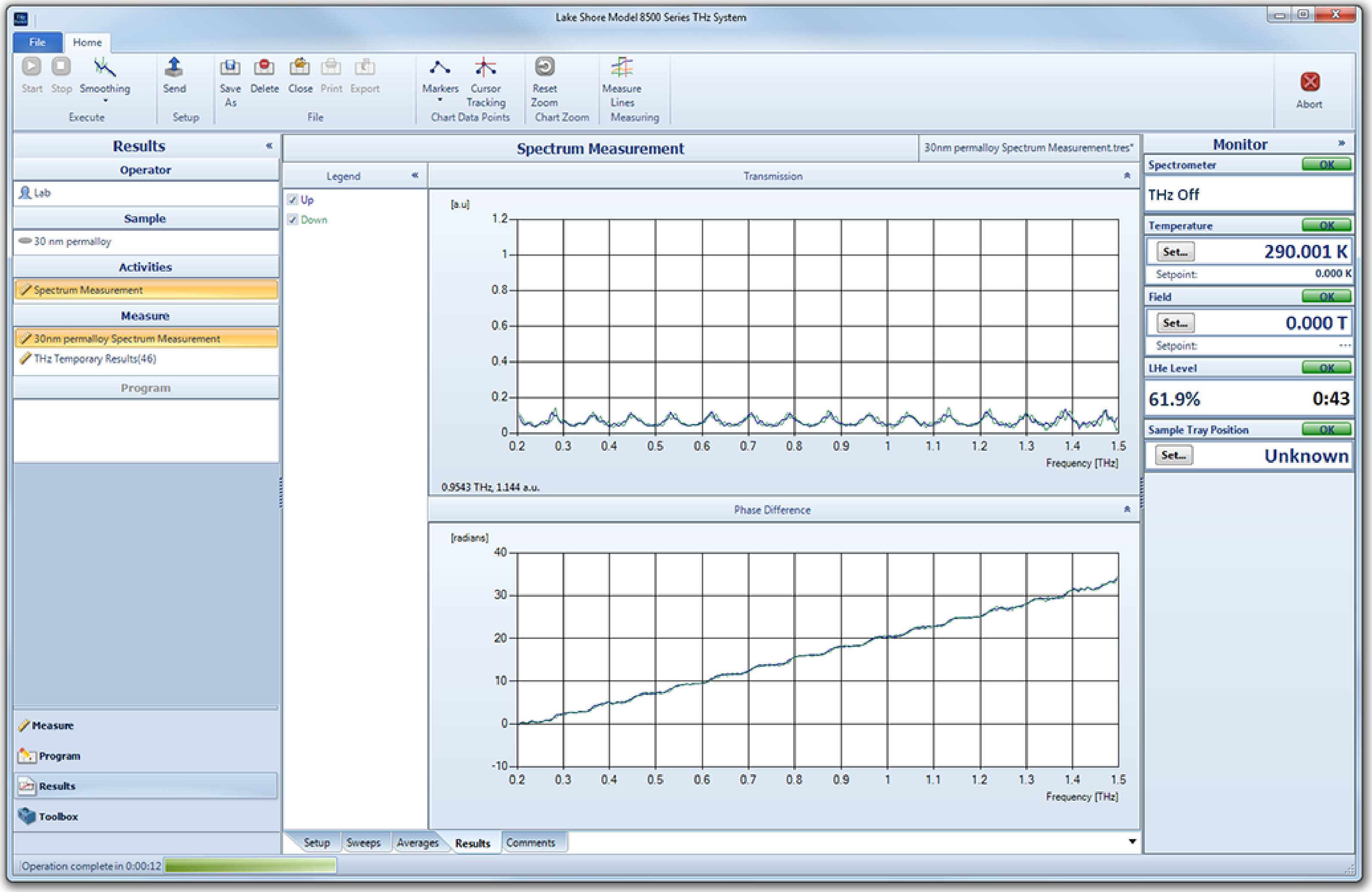


Integrated Software for Turn-key Operation

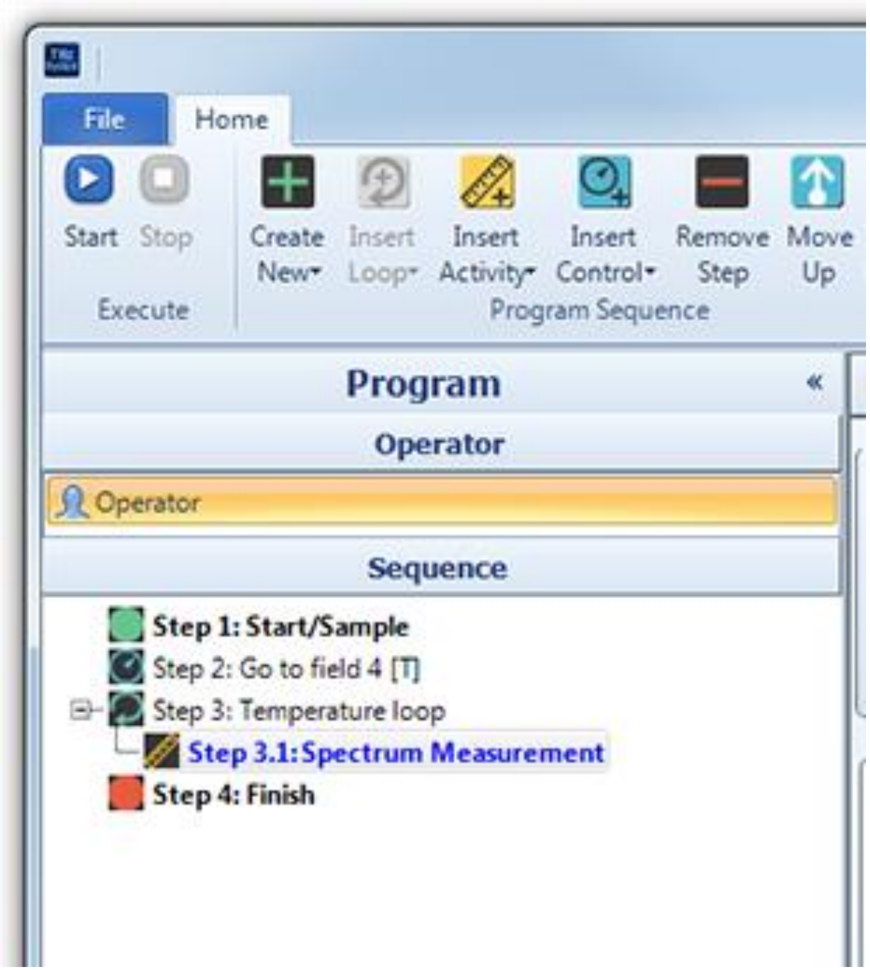
Sample | Reference | Background



Integrated Software for Turn-key Operation



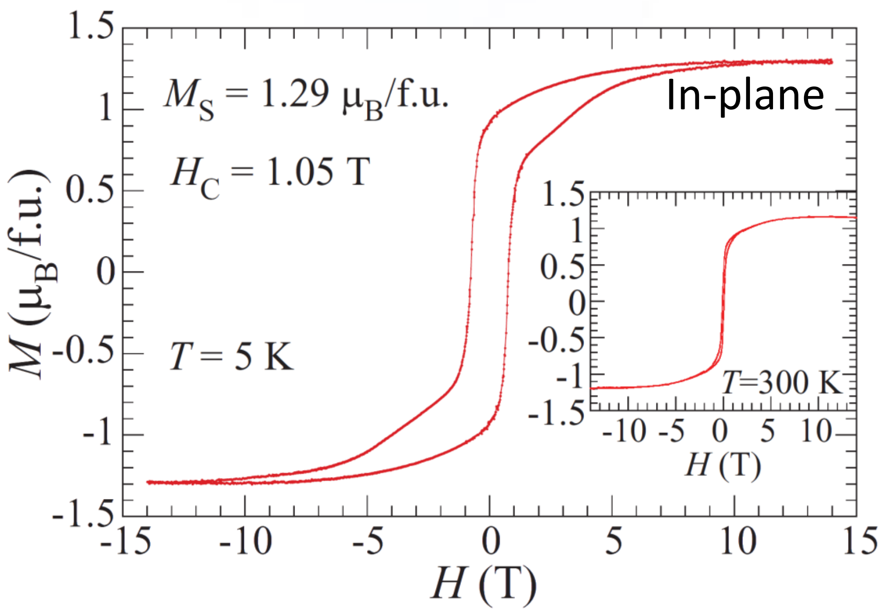
Integrated Software for Turn-key Operation

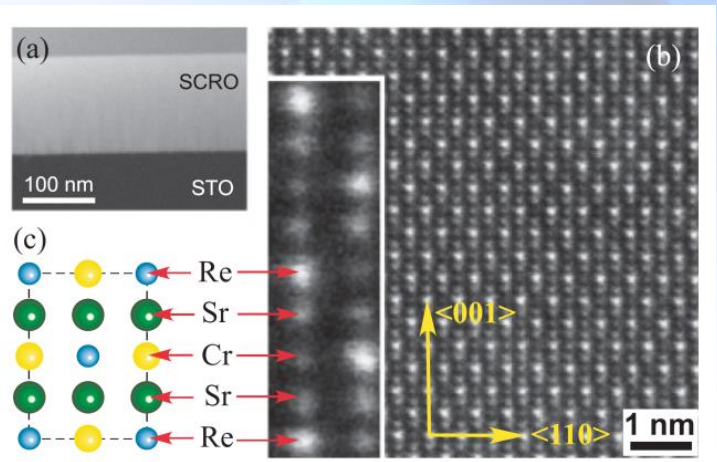


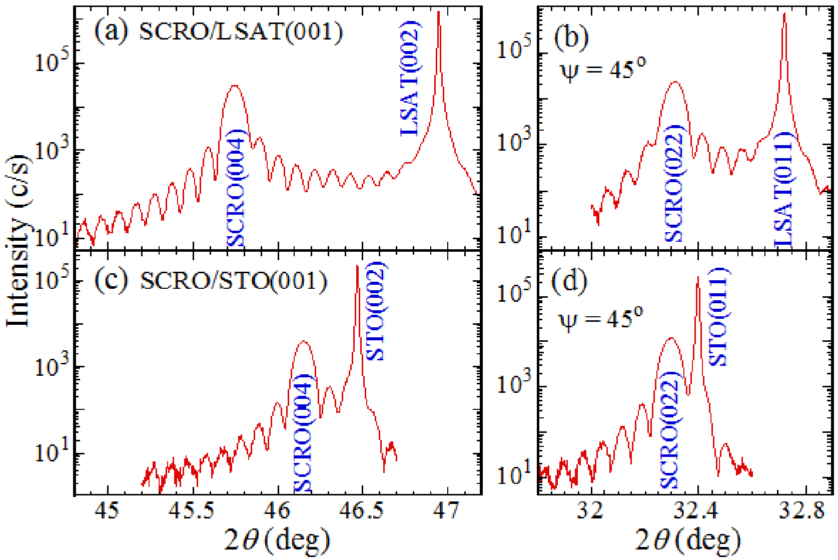
Lake Shore CRYOTRONICS

Case Study: Sr_2CrReO_6 Thin Films

- double-perovskite ferrimagnet (T_c = 635 K)
- M_s = 1.29 μ_B per f.u.
- Predicted 90% spin polarization
- Large anisotropy

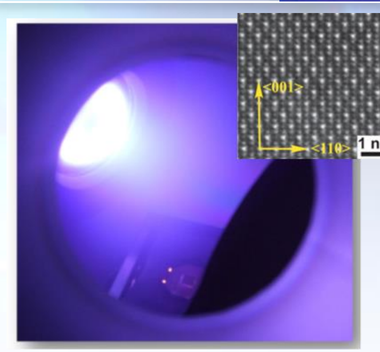






- Stoichiometric, epitaxial, and well ordered
- Well ordered films on STO and LSAT substrates

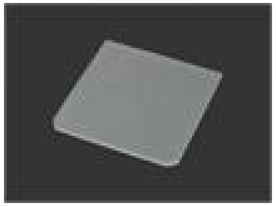
Case Study: Sr_2CrReO_6 Thin Films



<u>Stoichiometric, epitaxial, and well ordered</u>

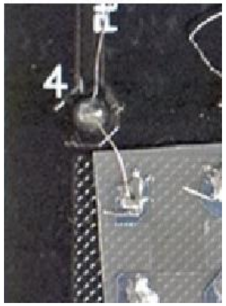
- Grown with off-axis magnetron sputtering

1 μm thickness ~ 20 hours



<u>Low Material yields</u>

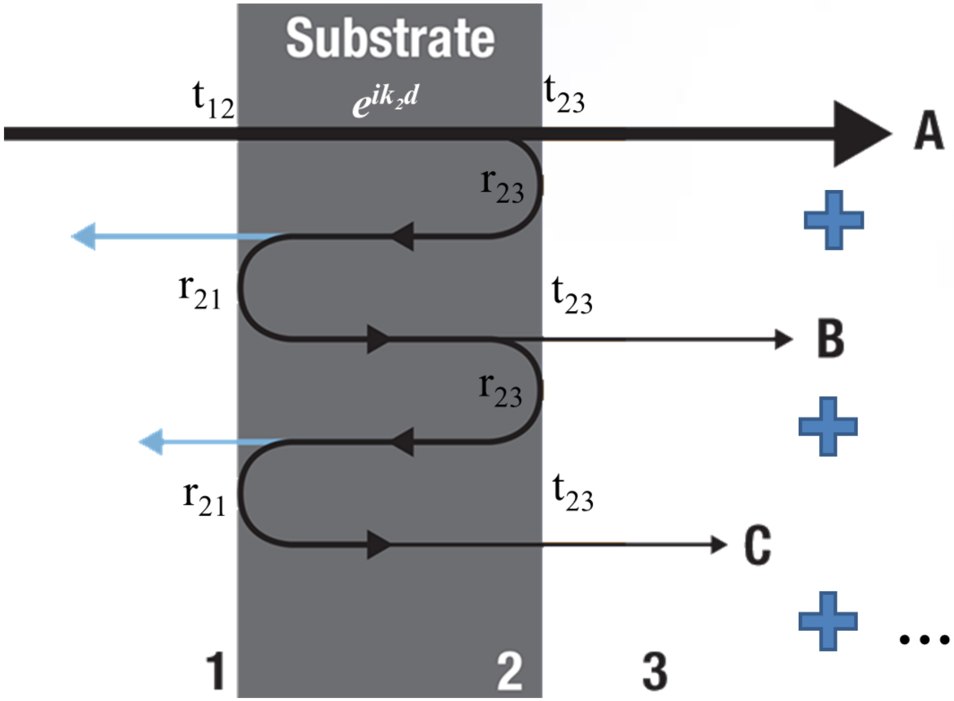
- 10 to 200 nm thick film on 10 x 10 mm substrate
- After characterization, wafer is diced & distributed for device manufacturing

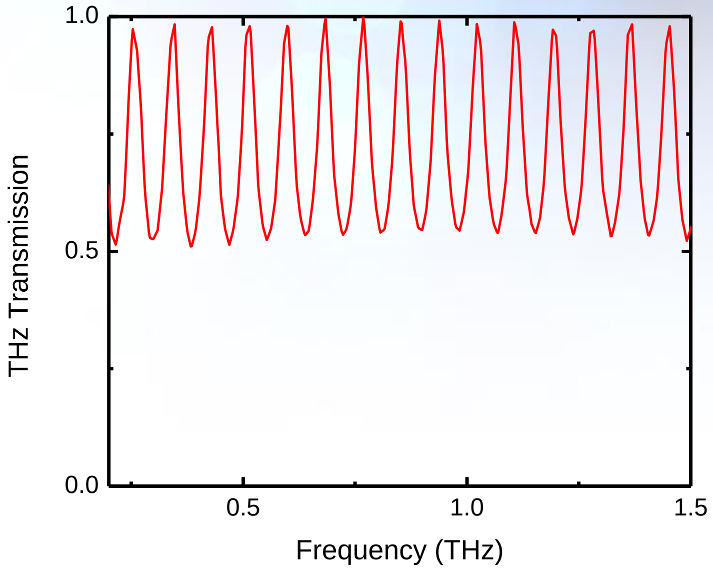


<u>Wafer real estate is at a premium</u>

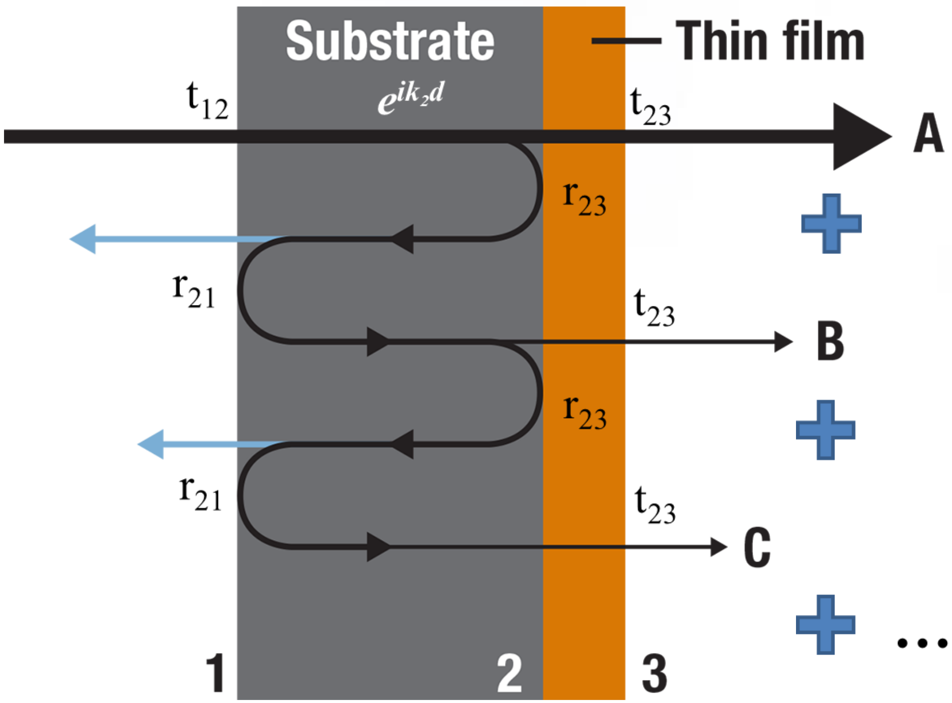
- Electrical contacts for material evaluation reduce number of devices – <u>non contact evaluation</u>
- Cryogenic characterization elucidates conduction mechanisms

CW-THz transmission

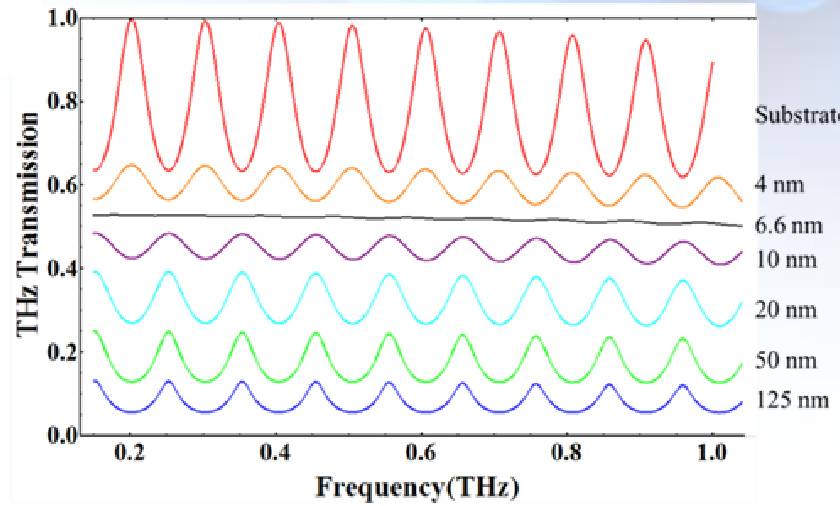


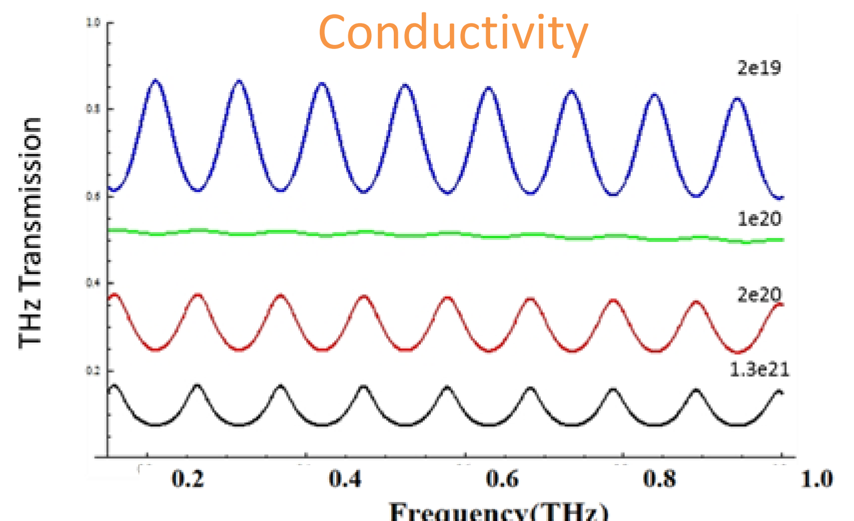


CW-THz Spectroscopy of Conductive Thin Films



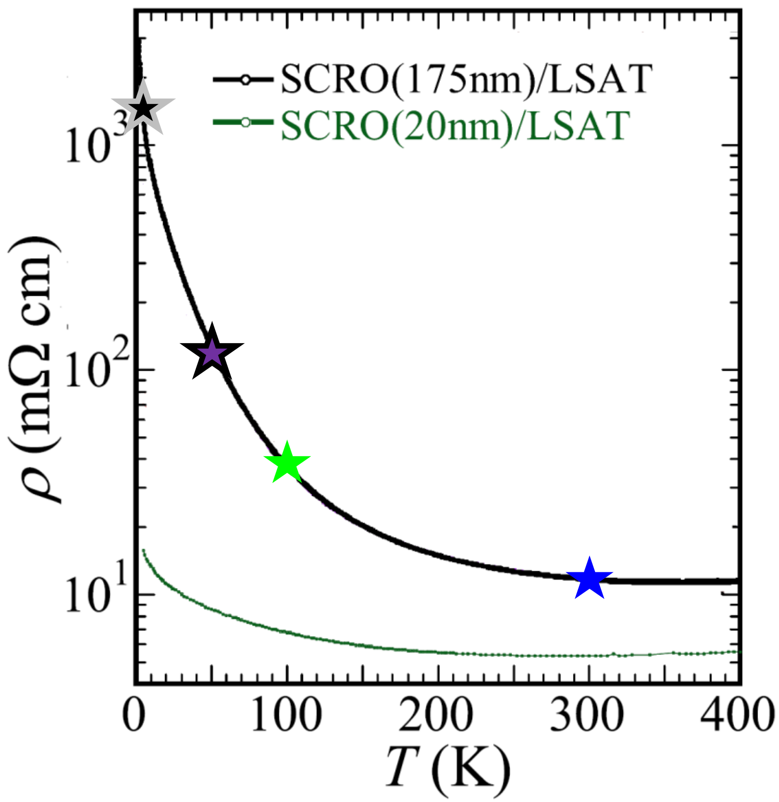
Thickness

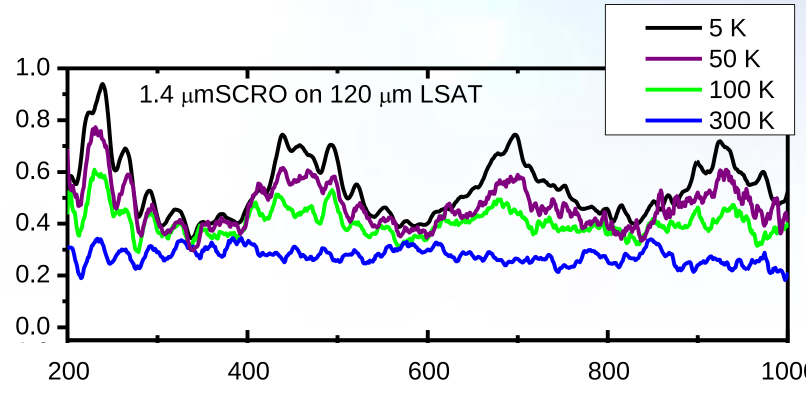


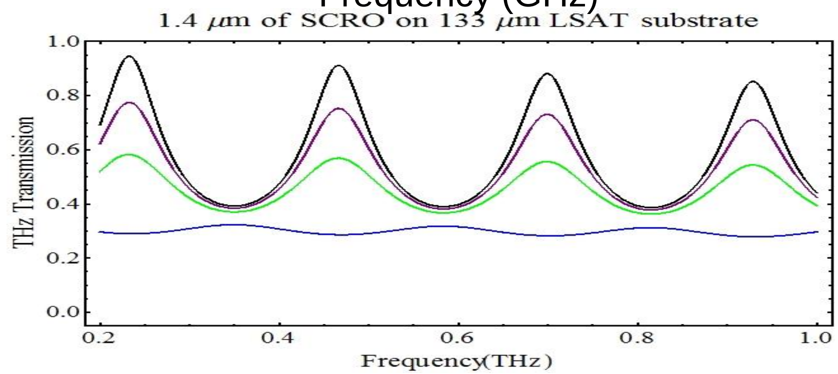


Ga-doped ZnO on ZnO

SCRO Film DC conductivity

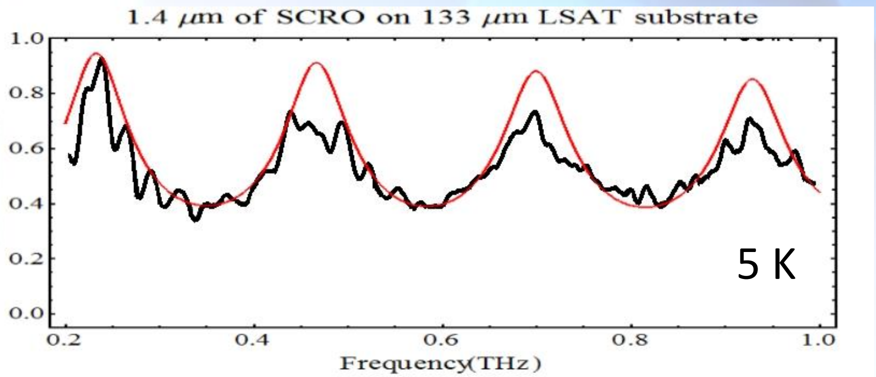






Variable Range Hopping Conductivity

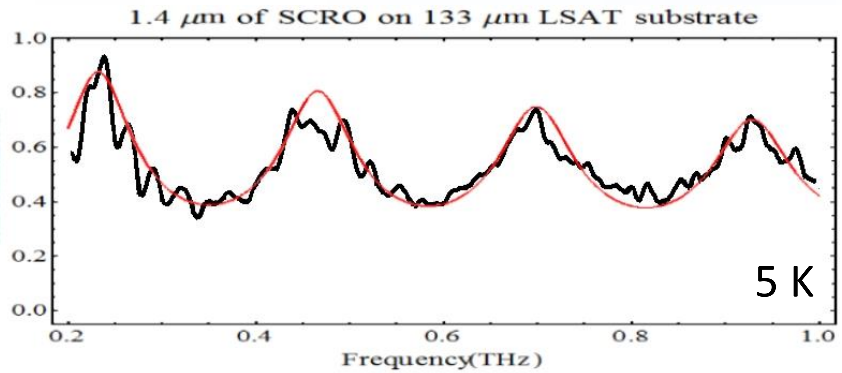
$$\sigma(\omega) = \sigma_{DC}$$



<u>Variable Range Hopping</u>

$$\sigma(\omega) = A(T)\omega^{s(T)} + \sigma_{DC}$$

$$A(5K) \sim \frac{1000}{2\pi} \qquad s(5K) \sim 0.8$$



N. F. Mott and E. A. Davis. *Electronic Processes in Non-Crystalline Materials.* Clarendon Press Oxford, 1971.

What's Next

Model 8500

THz System for Material Characterization

– Turn-key acquisition of temperature and field dependent THz spectra

Taking orders March 2014!

- Customer applications – samples
- Sponsored research program to develop turn-key analysis software for CW-THz spectra

Lake Shore CRYOTRONICS

Acknowledgements

Collaborators:

- Lake Shore
  Scott Yano & Richard Higgins
- EMCORE
  Joseph Demers
- The Ohio State University
  Center for Emergent Materials
  Chunhui Du & P. Chris Hammel
- Wright State University
  David Look & Tim Cooper
- University of Arizona
  Hao Xin & Min Liang
- IDCAST/UDRI
  G. E. Pacey

Funding:

- Ohio Third Frontier
  Ohio Department of Development
- USAF STTR Program

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