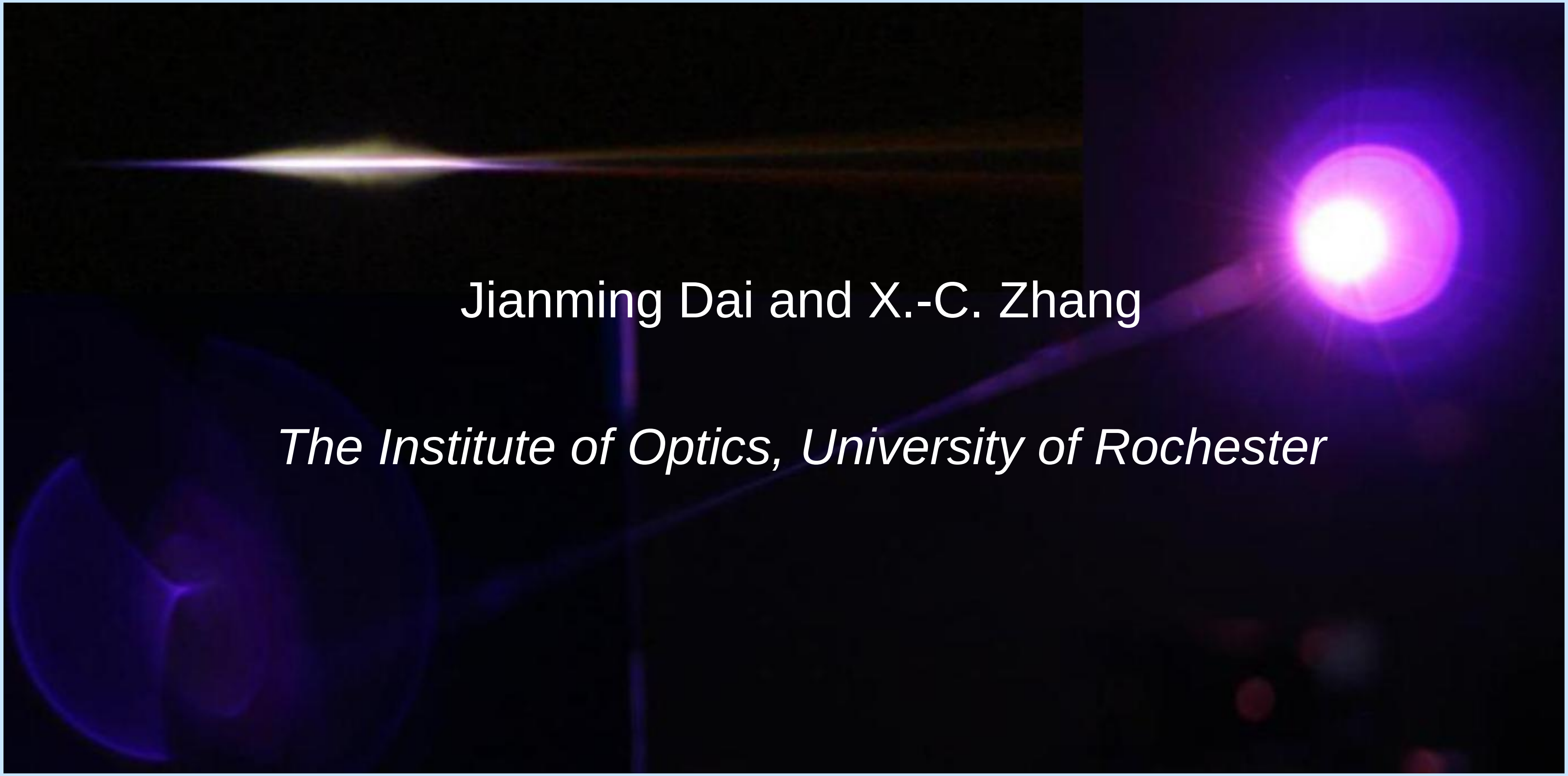
THz Wave Air Photonics:
Generation and Detection of Intense THz Waves with Laser-induced Plasma in Gaseous Media



Jianming Dai and X.-C. Zhang

The Institute of Optics, University of Rochester

Supported by ONR, DTRA, DHS, and NSF

Outline

- Brief history of THz wave air photonics
- THz wave generation with gaseous media
- THz wave detection with gas sensor
- Potential applications
- Summary

Brief History of THz Air Photonics

1993 **H. Hamster**, *et al.* – Subpicosecond, electromagnetic pulses from intense laser-plasma interaction

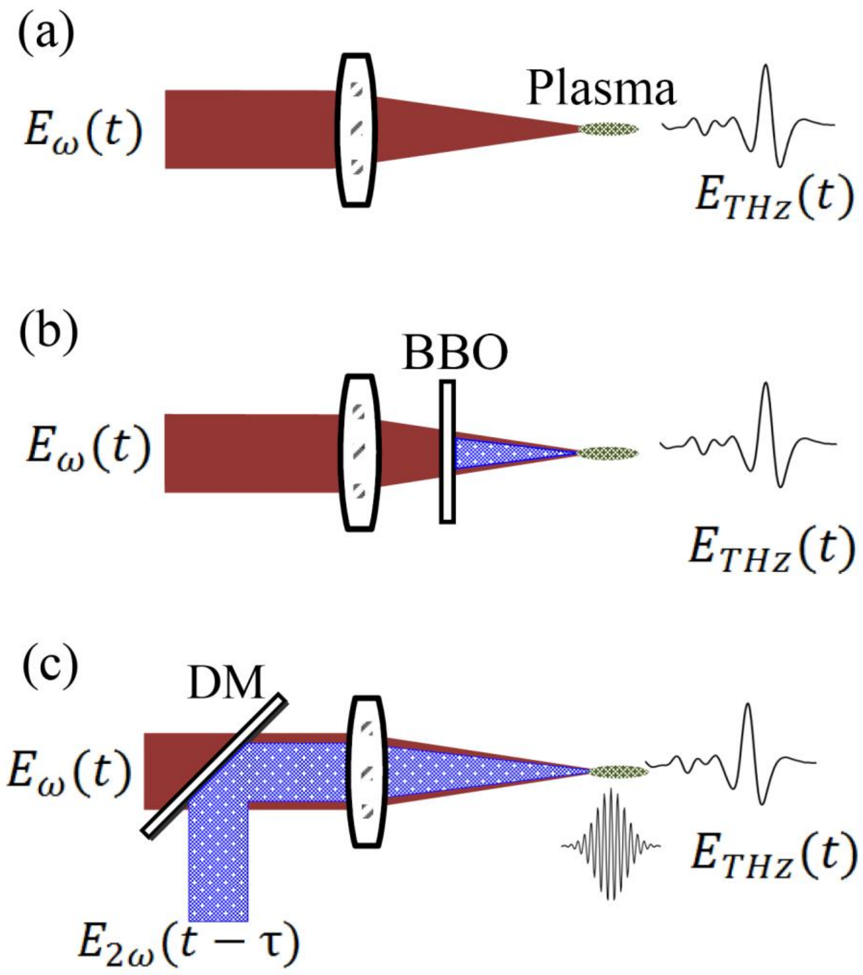
2000 **D.J. Cook**, *et al.* – Intense terahertz pulses by four-wave rectification in air

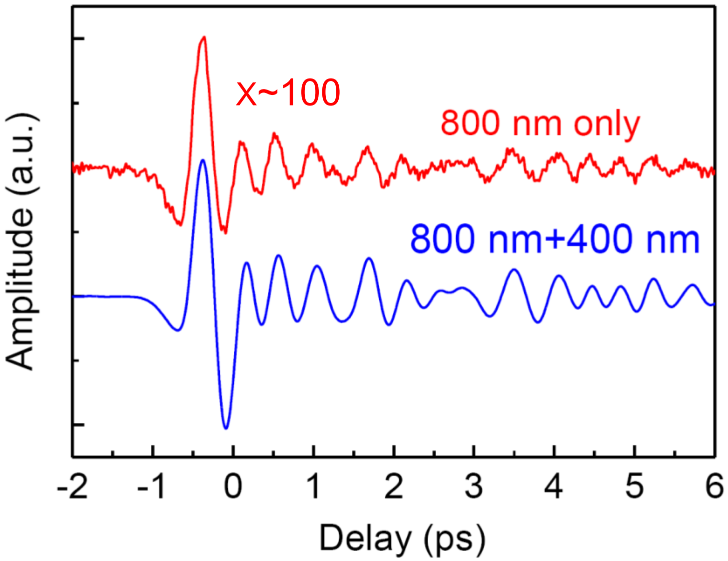
2005 **T. Bartel**, *et al.* – Generation of single-cycle THz transients with high electric-field amplitudes

2006 **X. Xie**, et al. – Coherent Control of THz Wave Generation in Ambient Air; **J. Dai**, et al. – Detection of Broadband Terahertz Waves with a Laser-Induced Plasma in Gases

- **M. Kress**, et al. – Determination of the Carrier-Envelope Phase of Few-Cycle Laser Pulses with Terahertz-Emission Spectroscopy
- **K. Y. Kim, et al.** – Coherent Control of Terahertz Supercontinuum Generation in Ultrafast Laser-Gas Interactions
- **Mysyrowicz'**s group in France and **Roskos**'s group in Germany are the most active groups working on THz emission from plasma Filaments
- **S. L. Chin**'s group in Canada reported their work in the field recently.

THz Wave Generation Methods with Air





Mechanism of THz Emission from Gas Plasma

- Four-wave mixing (FWM)

  *D. J. Cook, R. M. Hochstrasser, **Opt. Lett. 25**, 1210 (2000)*
  *X, Xie, J. Dai, and X.-C. Zhang, **Phys. Rev. Lett. 96,** 075005 (2006)*

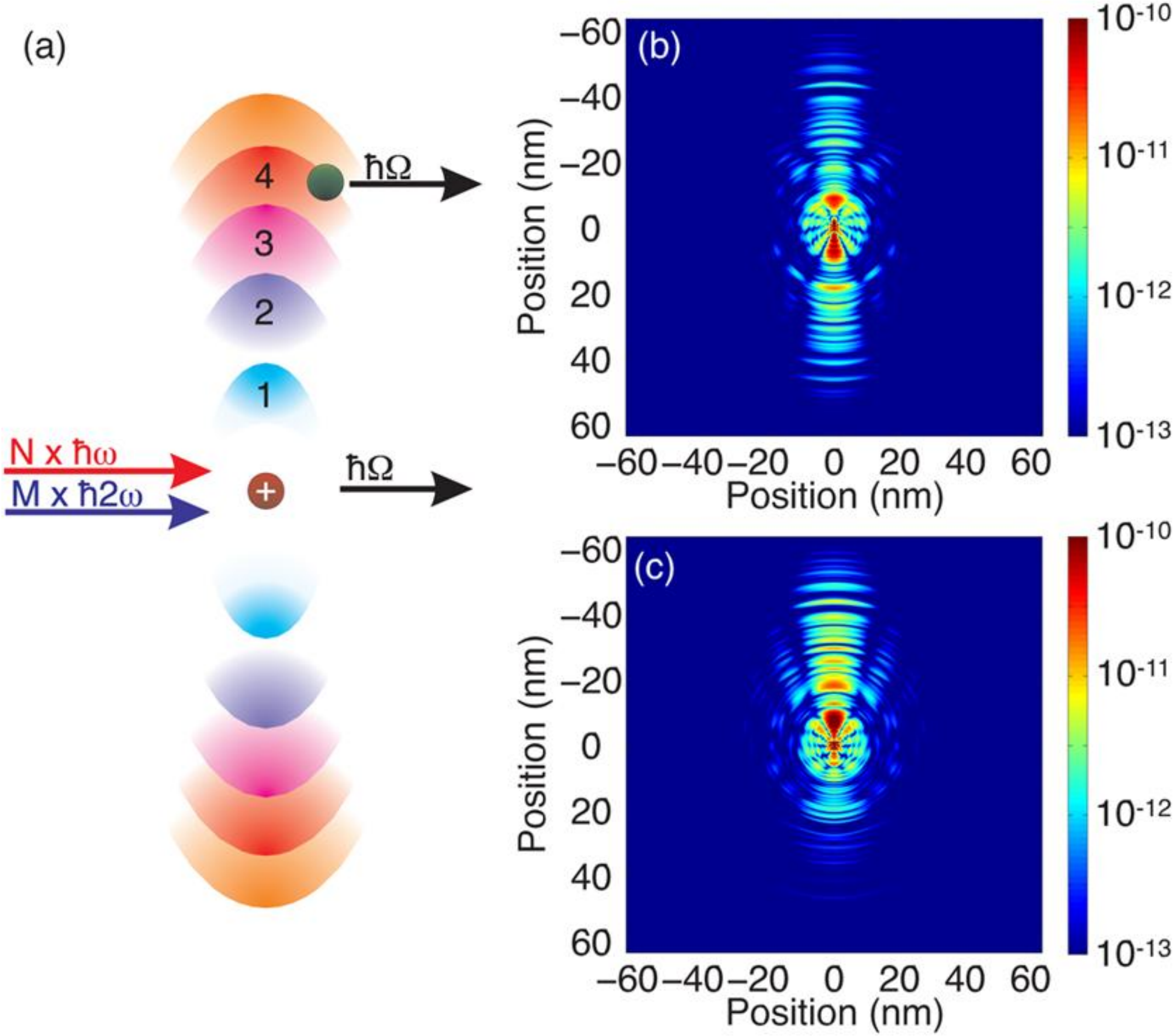
- Asymmetric transient current (ATC)

  *M. Kress, et al., **Opt. Lett. 29**, 1120 (2004)*
  *K. Y. Kim, et al., **Opt. Express 15**, 4577 (2007)*

- Quantum mechanical simulation

  *N. Karpowicz and X.-C. Zhang, **Phys. Rev. Lett. 102,** 093001 (2009)*

Quantum Mechanical Model

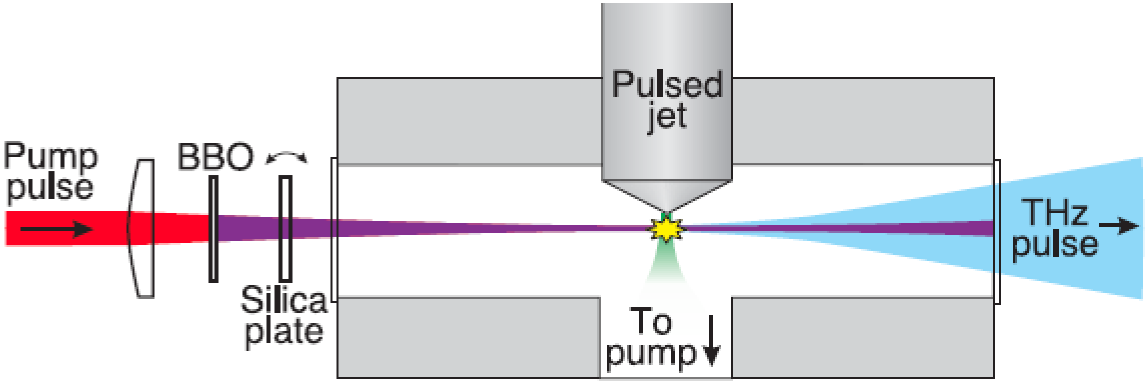


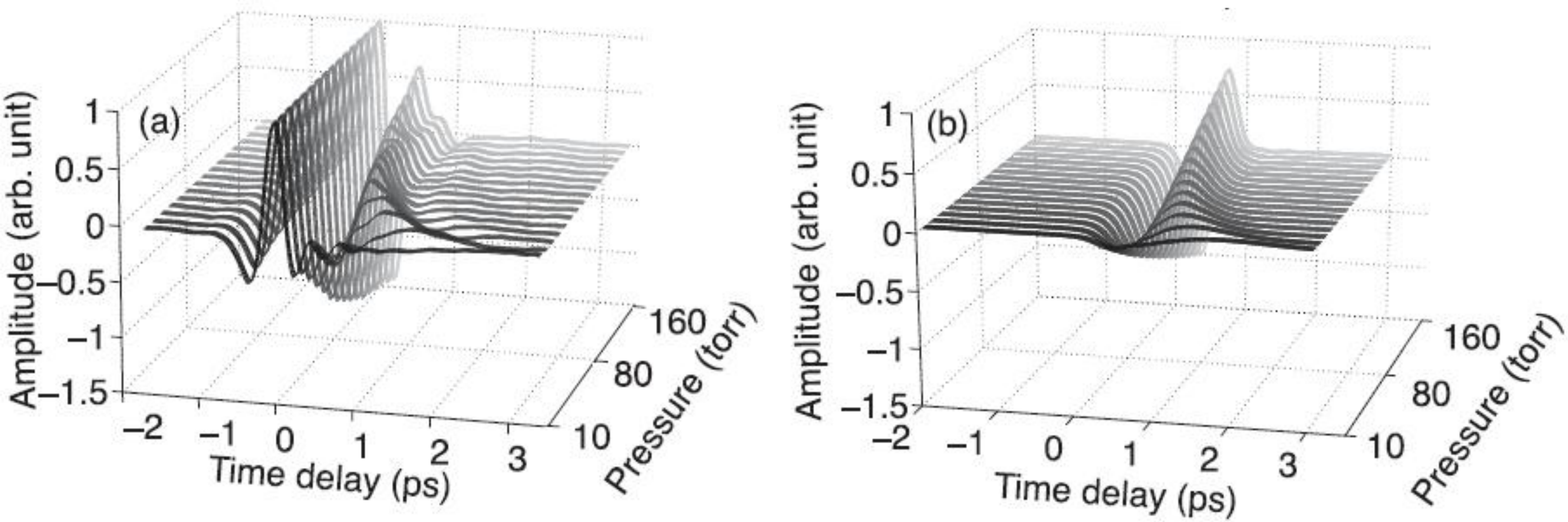
Relative Phase: $5\pi/12$

Relative Phase: $11\pi/12$

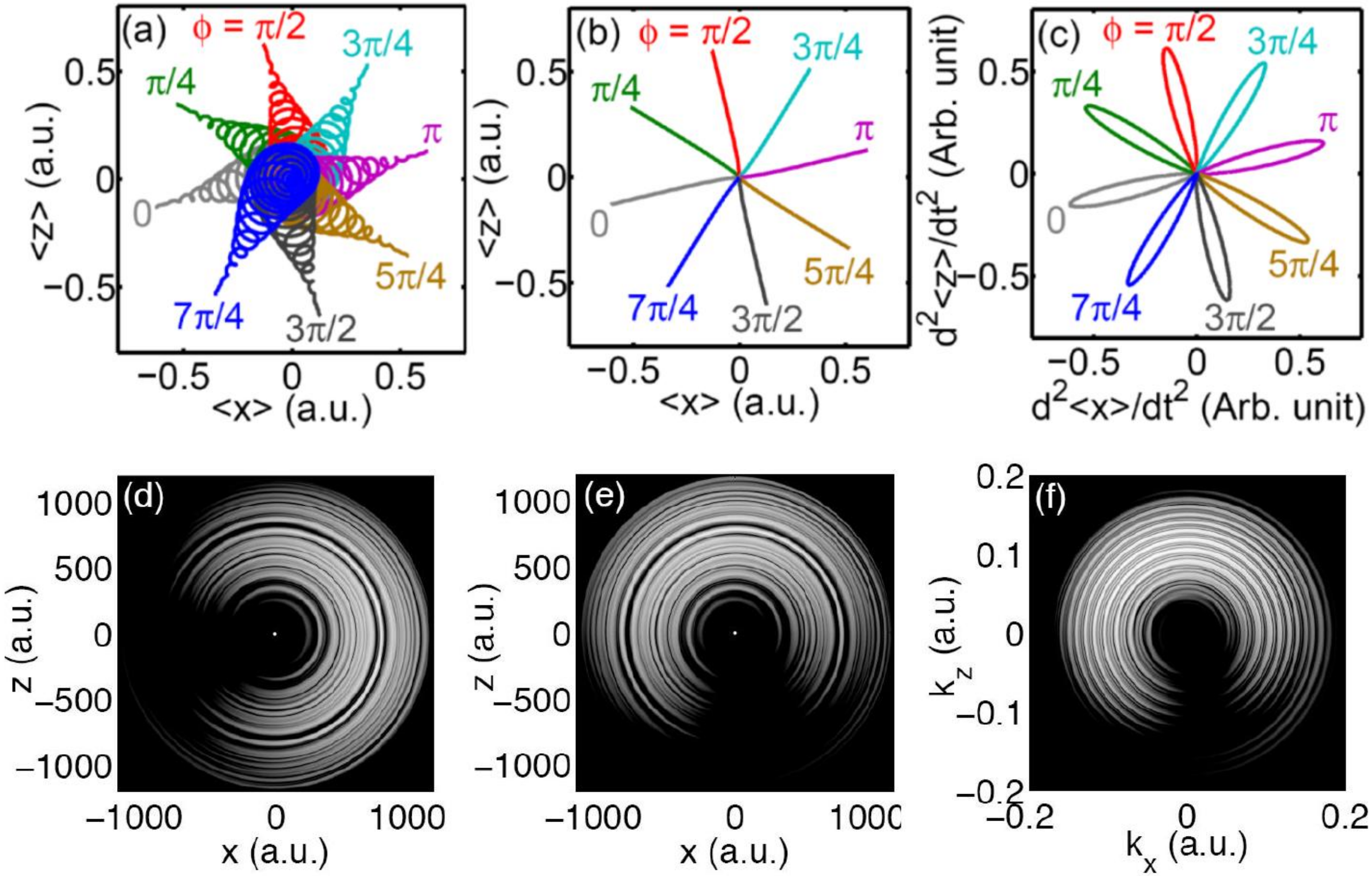
Quantum Mechanical Model-continue

*N. Karpowicz and X.-C. Zhang, **Phys. Rev. Lett. 102,** 093001 (2009)*





3-D Quantum Mechanical Simulation of electron behavior with two-color excitation

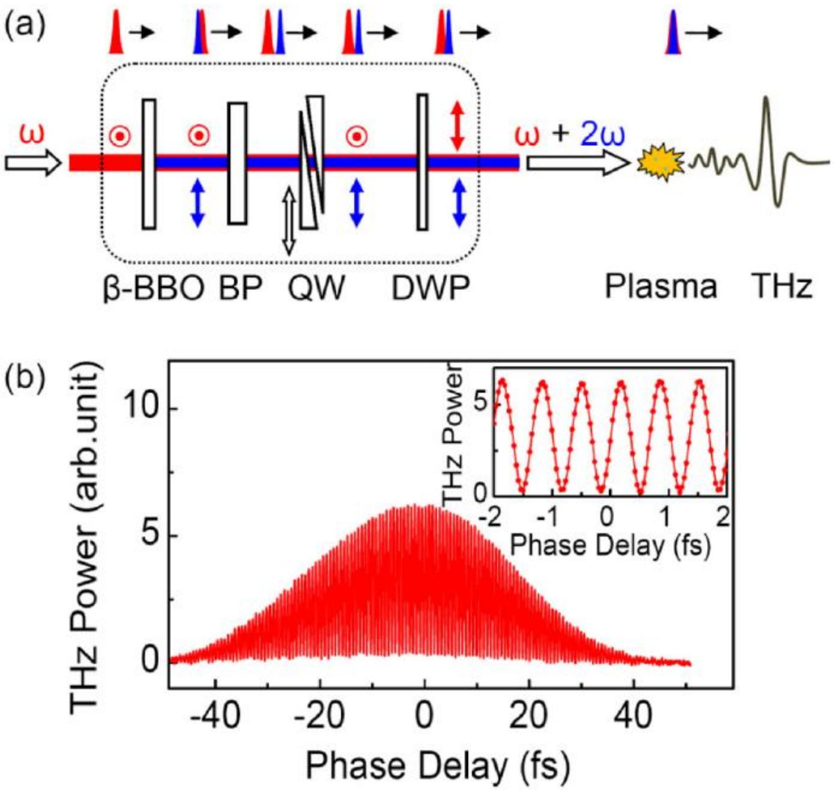


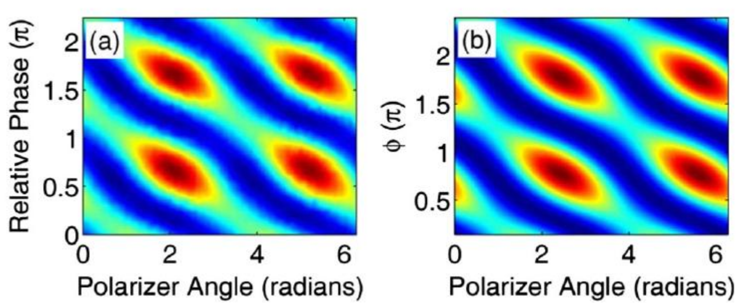
pi

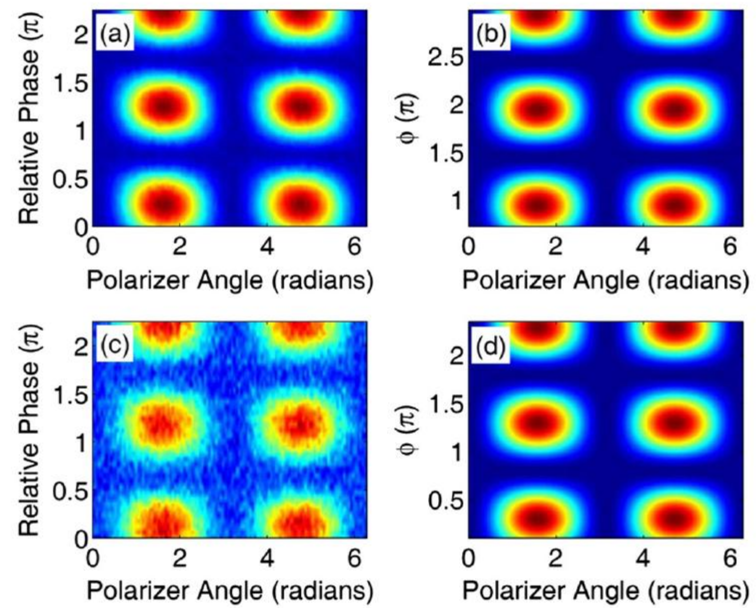
pi/2

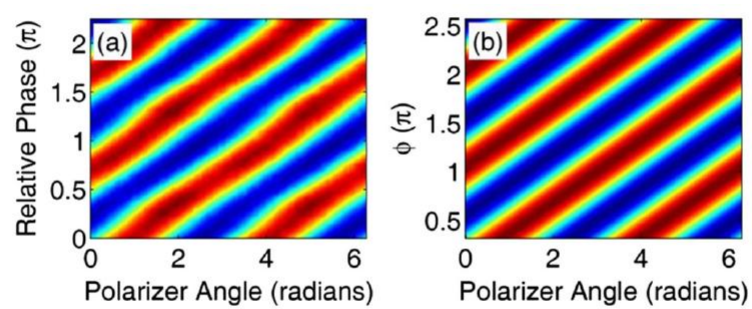
pi/2

Coherent Control with an In-Line Phase compensator









J. Dai, N. Karpowicz and X.-C. Zhang, ***Phys. Rev. Lett. 103,*** *023001 (2009)*

Highlights on Nature Photonics and OPN

news & views

PLASMA PHOTONICS

Harnessing terahertz polarization

The polarization of terahertz pulses emitted from a laser-generated plasma can be rotated at will by changing the relative delay between ultrashort red and blue excitation pulses. The result is a fast and convenient method of polarization control.

Michael Woerner and Klaus Reimann

Nature Photonics *3, 495 (2009)*

One of the 36 significant findings in a peer-reviewed journal over the course of the past year in optics

'09 TERAHERTZ TECHNOLOGY

Optical Manipulation of THz Wave Polarization in Two-Color Laser-Induced Gas Plasma

Jianming Dai, Nicholas Karpowicz and X.-C. Zhang

Optics in 2009, ***Optics and Photonics News (OPN)*** *20, 36 (2009)*

Coherent Control of Terahertz Polarization

PRL **103,** 023902 (2009) PHYSICAL REVIEW LETTERS week ending 10 JULY 2009

Coherent Terahertz Polarization Control through Manipulation of Electron Trajectories

Haidan Wen[1] and Aaron M. Lindenberg[1,2]

[1]*PULSE Institute, SLAC National Accelerator Laboratory, Menlo Park, California, 94025, USA*
[2]*Department of Materials Science and Engineering, Stanford University, Stanford, California, 94305, USA*
(Received 3 March 2009; published 7 July 2009; publisher error corrected 1 September 2009)

PRL **103,** 023001 (2009) PHYSICAL REVIEW LETTERS week ending 10 JULY 2009

Coherent Polarization Control of Terahertz Waves Generated from Two-Color Laser-Induced Gas Plasma

Jianming Dai, Nicholas Karpowicz, and X.-C. Zhang*

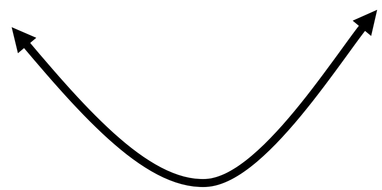
Center for Terahertz Research, Rensselaer Polytechnic Institute, Troy, New York 12180, USA
(Received 4 May 2009; published 10 July 2009)

Generation & Detection of THz Wave by $\chi^{(3)}$

*X. Xie, J. Dai, and X.-C. Zhang, **Phys. Rev. Lett. 96**, 075005 (2006)*

Generation (FWM):

$$E_{THz}(t) \propto \chi^{(3)} E_{2\omega}(t) E^*_{\omega}(t) E^*_{\omega}(t) \cos(\phi)$$



exchange

Detection (ABCD):

$$E_{2\omega}(t) \propto \chi^{(3)'} E_{THz}(t) E^*_{\omega}(t) E^*_{\omega}(t) \cos(\phi')$$

TFISH: THz-field induced Second harmonic generation

*J. Dai, X. Xie, and X.-C. Zhang, **Phys. Rev. Lett. 97**, 103903 (2006)*

THz Detection in Air

- THz Detection in Air (TFISH)

$$E_{2\omega}^{THz} = \chi^{(3)} E_{THz} E_{\omega} E_{\omega}$$

$$I_{2\omega}^{THz} \propto I_{THz}$$

- Since the SH power, not the field, is measured, the signal should be incoherent (phase information is lost);

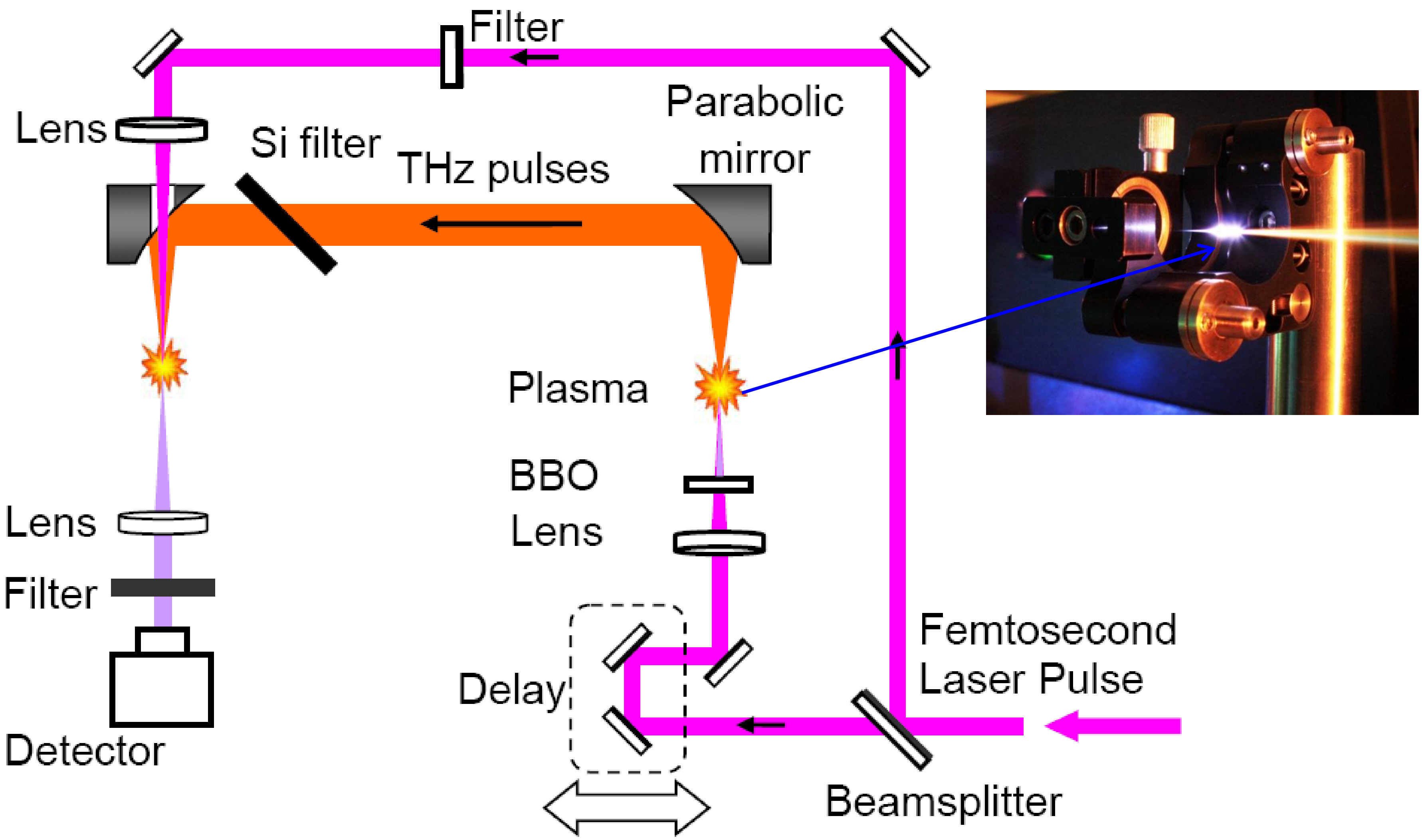
- A second harmonic local oscillator from plasma interferes with the signal, causing a coherent cross term:

$$I_{2\omega} = \left\langle E_{2\omega}^{2} \right\rangle = \left\langle (E_{2\omega}^{THz} + E_{2\omega}^{LO})^{2} \right\rangle = \left\langle E_{2\omega}^{THz^2} \right\rangle + 2\left\langle E_{2\omega}^{THz} E_{2\omega}^{LO} \right\rangle + \left\langle E_{2\omega}^{LO^2} \right\rangle$$

- **THz A**ir-**B**reakdown **C**oherent **D**etection **(THz-ABCD)**

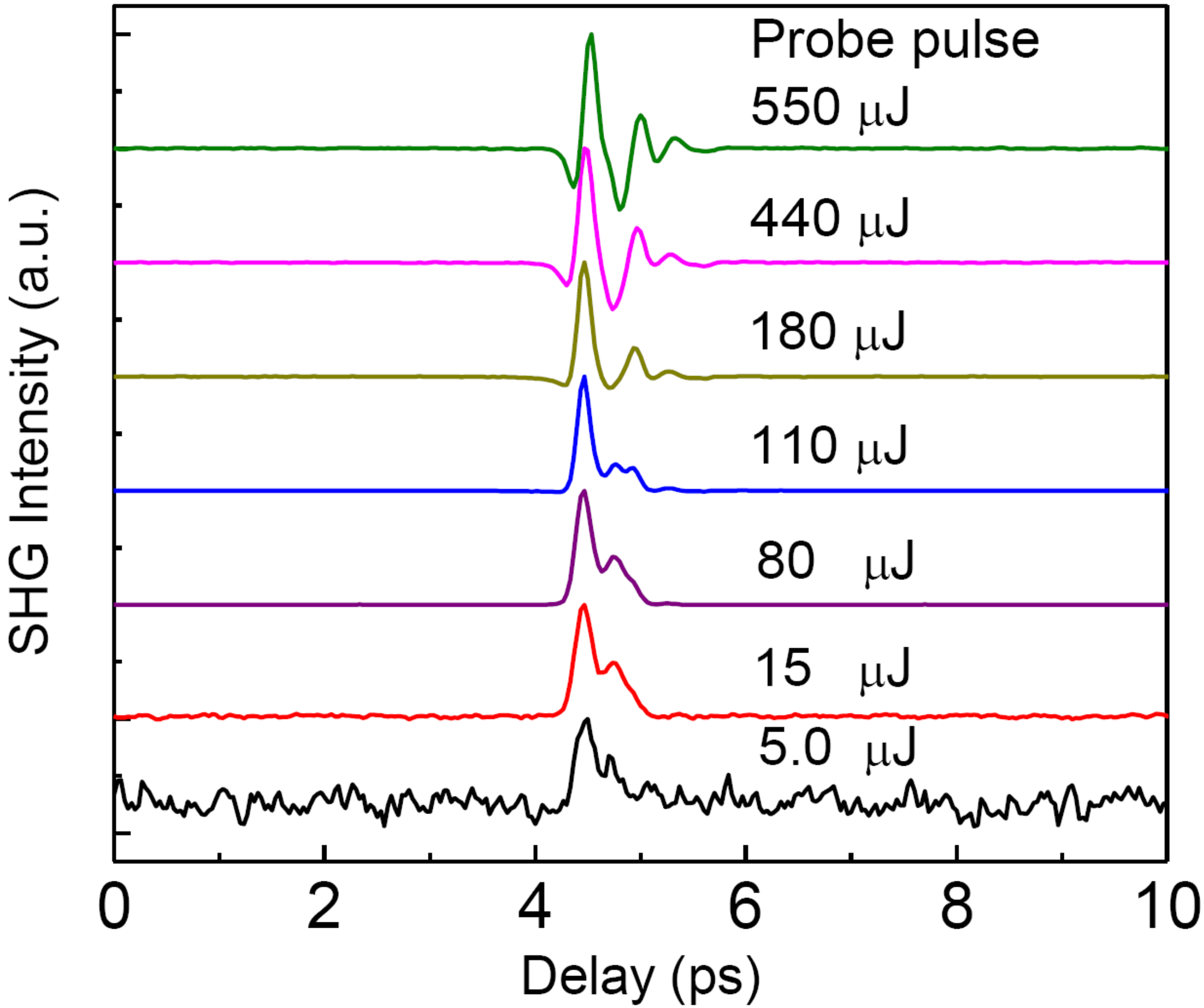
$$I_{2\omega} \propto E_{THz}$$

Standard THz-ABCD Setup



*J. Dai, X. Xie, and X.-C. Zhang, **Phys. Rev. Lett. 97**, 103903 (2006)*

Role of SH Local Oscillator



*J. Dai, J. Liu, and X.-C. Zhang, **IEEE JSTQE, 17**, 183 (2011)*

Heterodyne Detection in Air

- Basic idea: Introduce a SH local oscillator that we can control.
  - Utilizing an external DC-field to induce second harmonic as the local oscillator to realize Heterodyne Detection

$$I_{2\omega} = \left\langle E_{2\omega}^{2} \right\rangle = \left\langle (E_{2\omega}^{THz} + E_{2\omega}^{LO})^{2} \right\rangle = \left\langle {E_{2\omega}^{THz}}^{2} \right\rangle + \boxed{2\left\langle E_{2\omega}^{THz} E_{2\omega}^{LO} \right\rangle} + \left\langle {E_{2\omega}^{LO}}^{2} \right\rangle$$

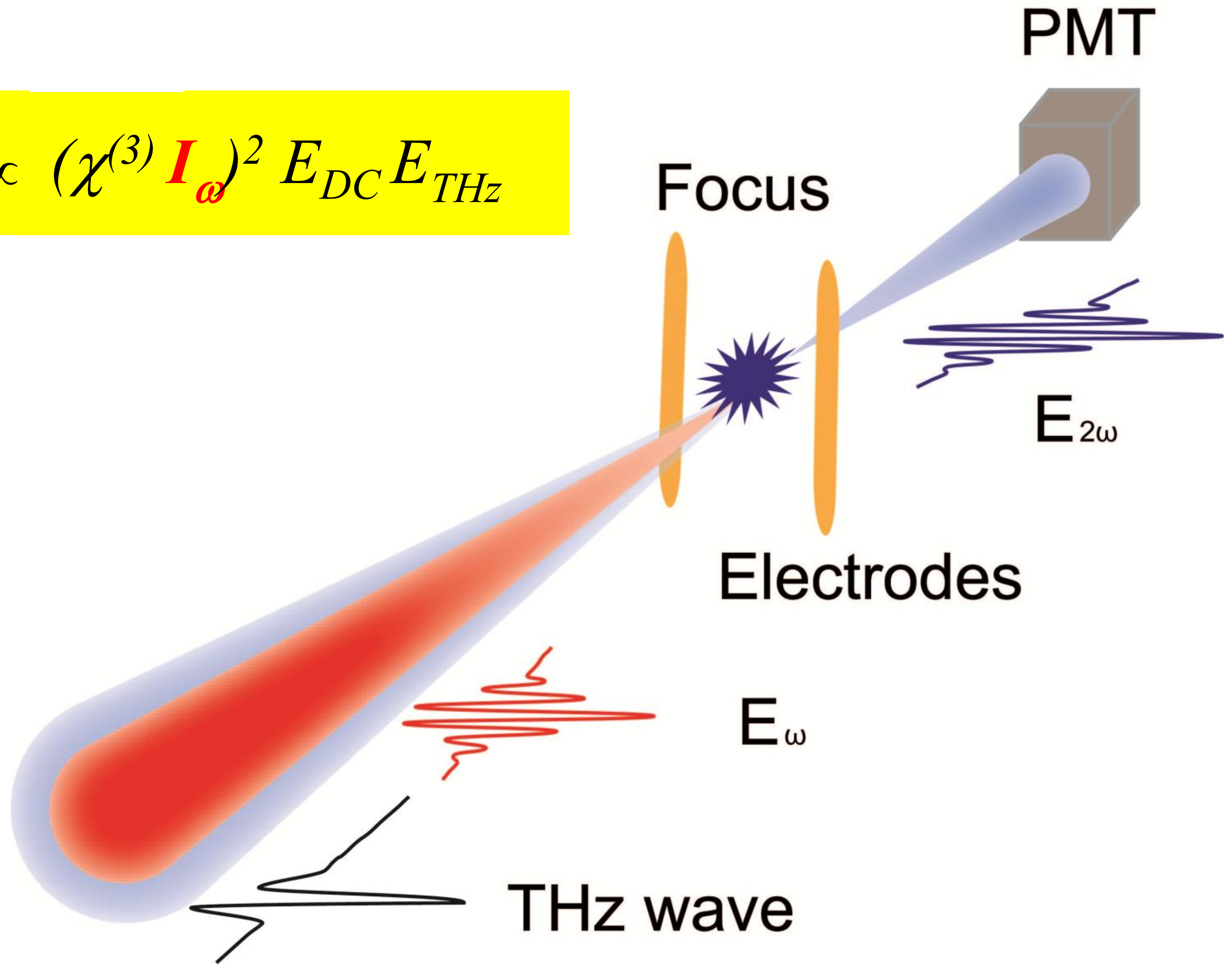
1 kHz 500 Hz 1 kHz

THz **A**ir-**B**iased **C**oherent **D**etection **(THz-ABCD)**

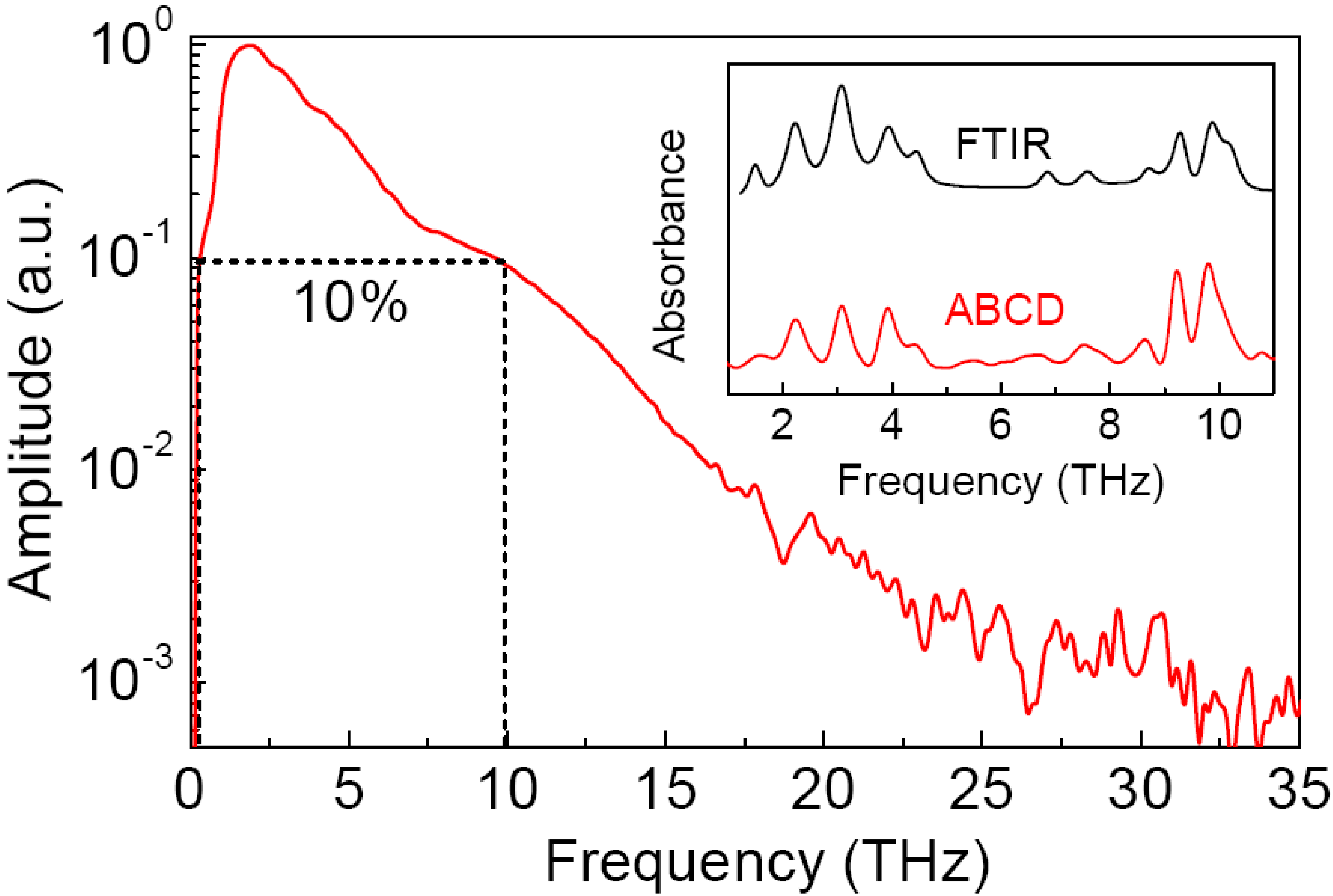
N. Karpowicz, J. Dai, X.F. Lu, et al., ***Appl. Phys. Lett. 92****, 011131 (2008)*

Heterodyne THz Detection with a Local Oscillator

$$I_{2\omega} \propto (\chi^{(3)} I_{\omega})^2 E_{DC} E_{THz}$$



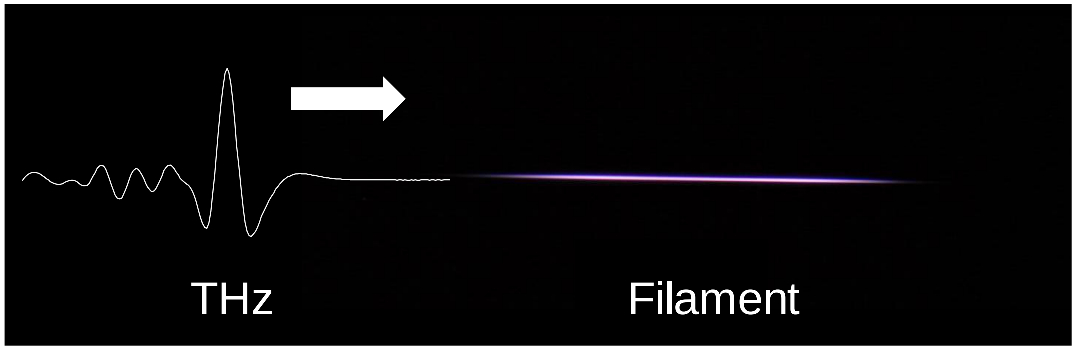
Broadband Detection Covers THz Gap



Laser pulse: ~ 80 fs, ~600 μJ. **Detection bandwidth only limited by the probe pulse duration**

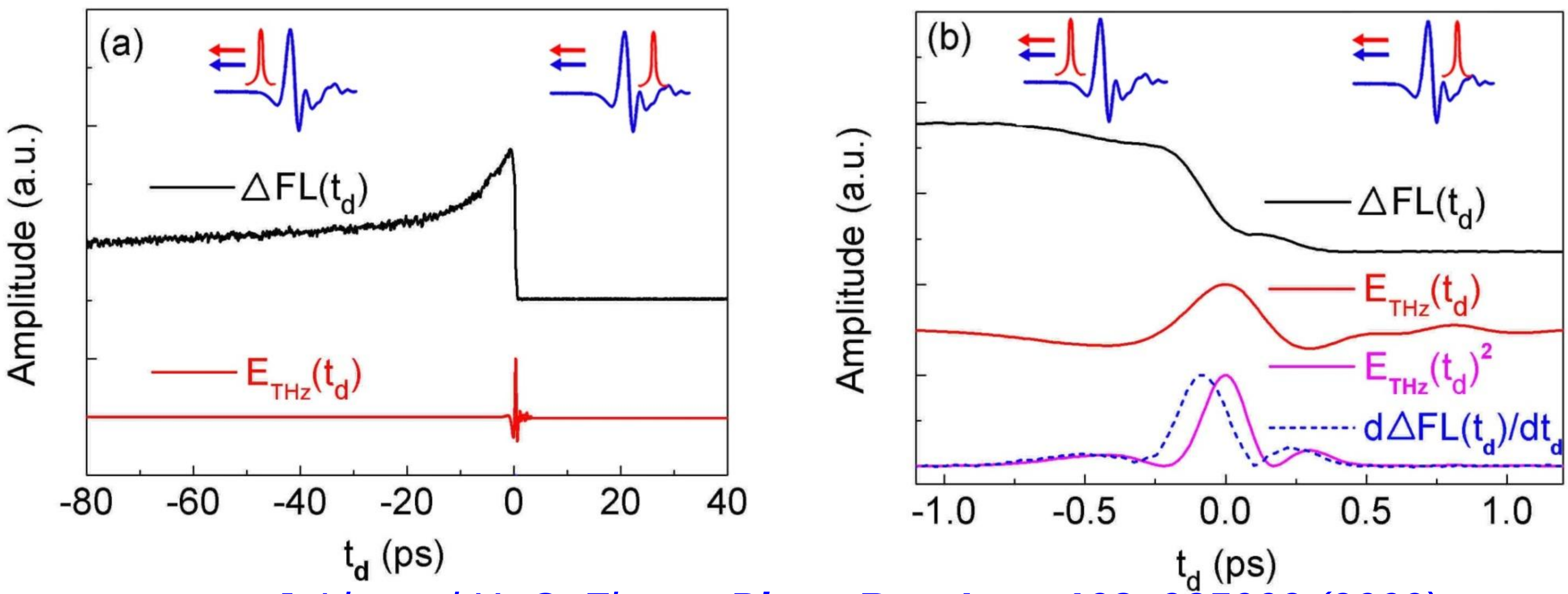
ZAP: Zomega Air Photonics

THz Radiation Enhanced Emission of Fluorescence (THz-REEF)



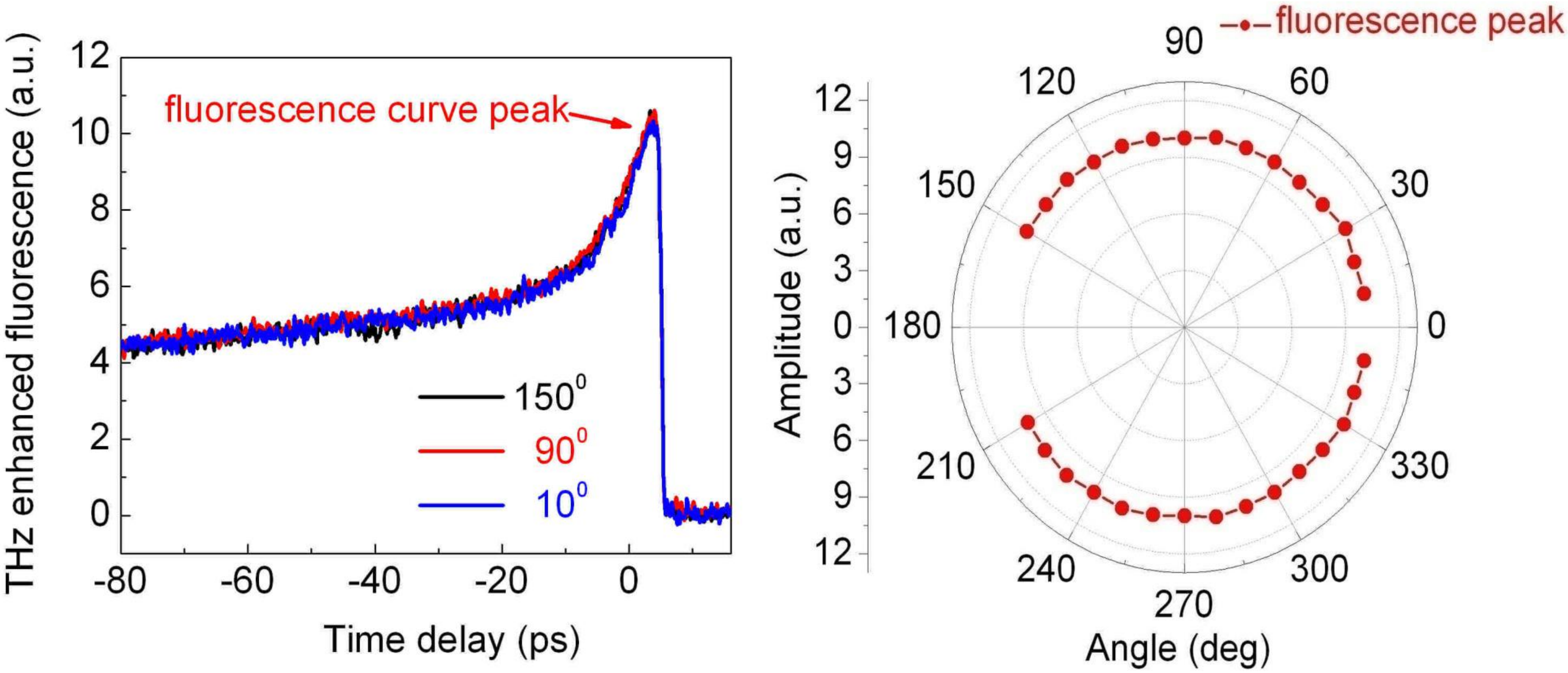
ω : $\frac{d(FL)}{dt} \propto I_{THz}$

$\omega + 2\omega$: $\frac{d(FL)}{dt} \propto E_{THz}$



J. Liu and X.-C. Zhang, ***Phys. Rev. Lett. 103****, 235002 (2009)*

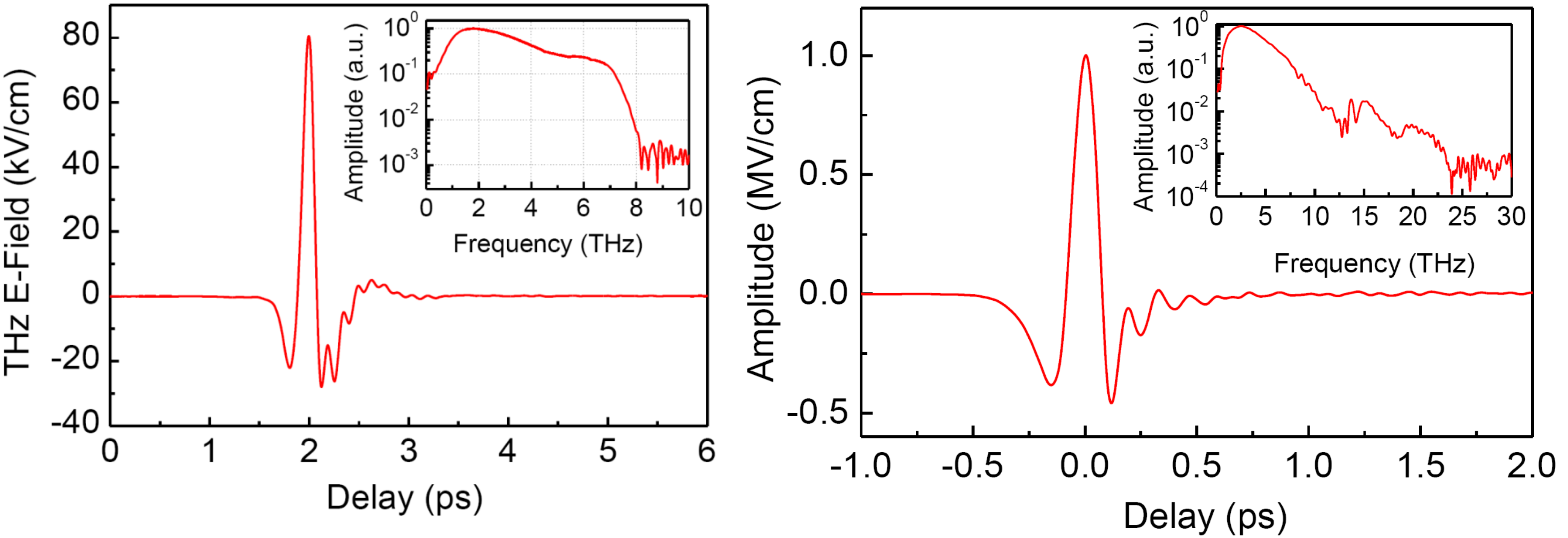
Fluorescence Enhancement is Isotropic



Optical pulse energy 100 μJ, THz peak field 100kV/cm

Applications—Linear and Nonlinear THz Spectroscopy with THz Air Photonics

H. Wen, M. Wiczer, A.M. Lindenberg, ***Phys. Rev. B 78****, 125203 (2008)*



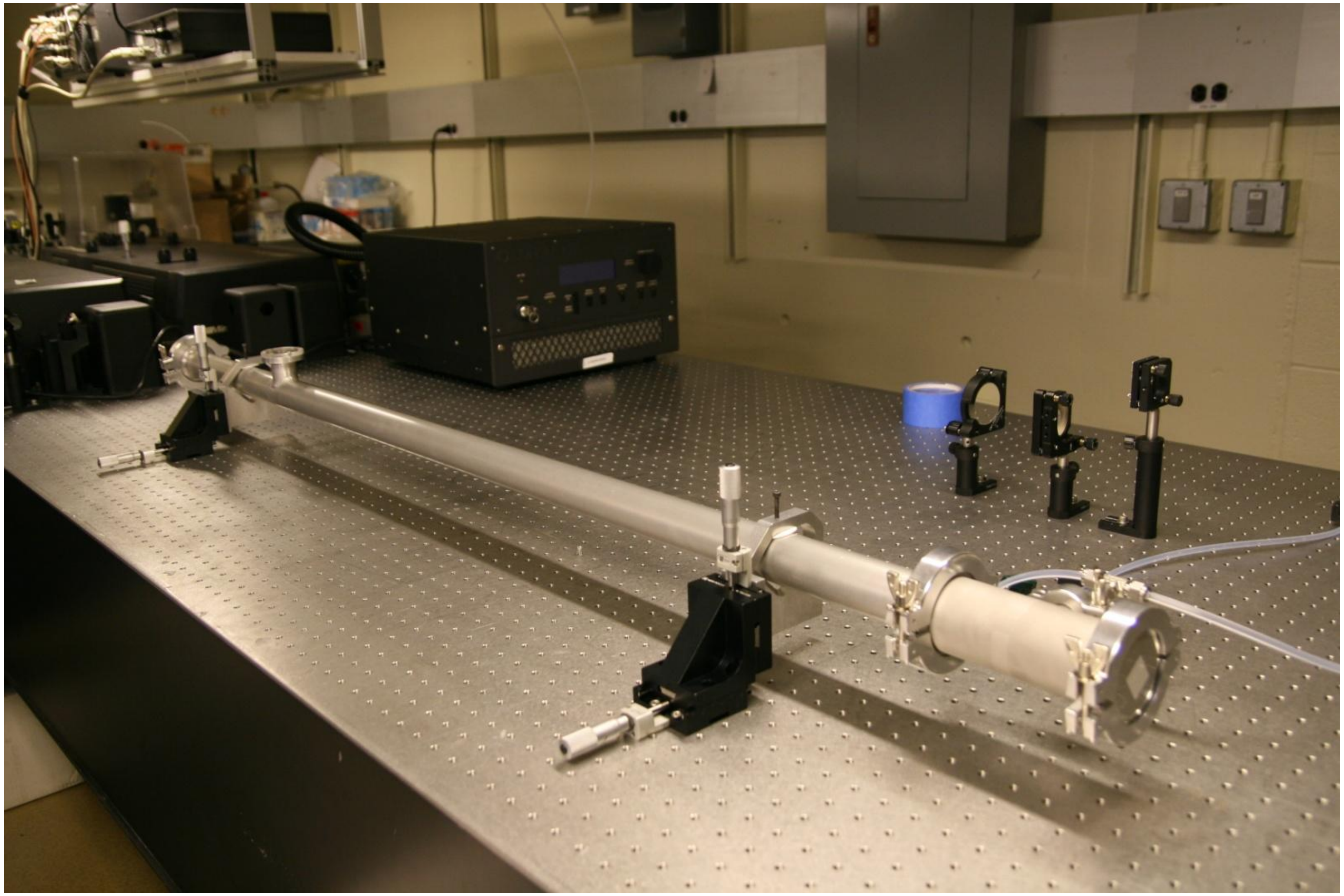
Detector: 0.3 mm <110> GaP.
Lock-in time constant: 300 ms
Laser pulse: ~100 fs, ~600 μJ

Detector: 0.106 mm <110> GaP.
Lock-in time constant: 100 ms
Laser pulse: ~28 fs, >2.0 mJ

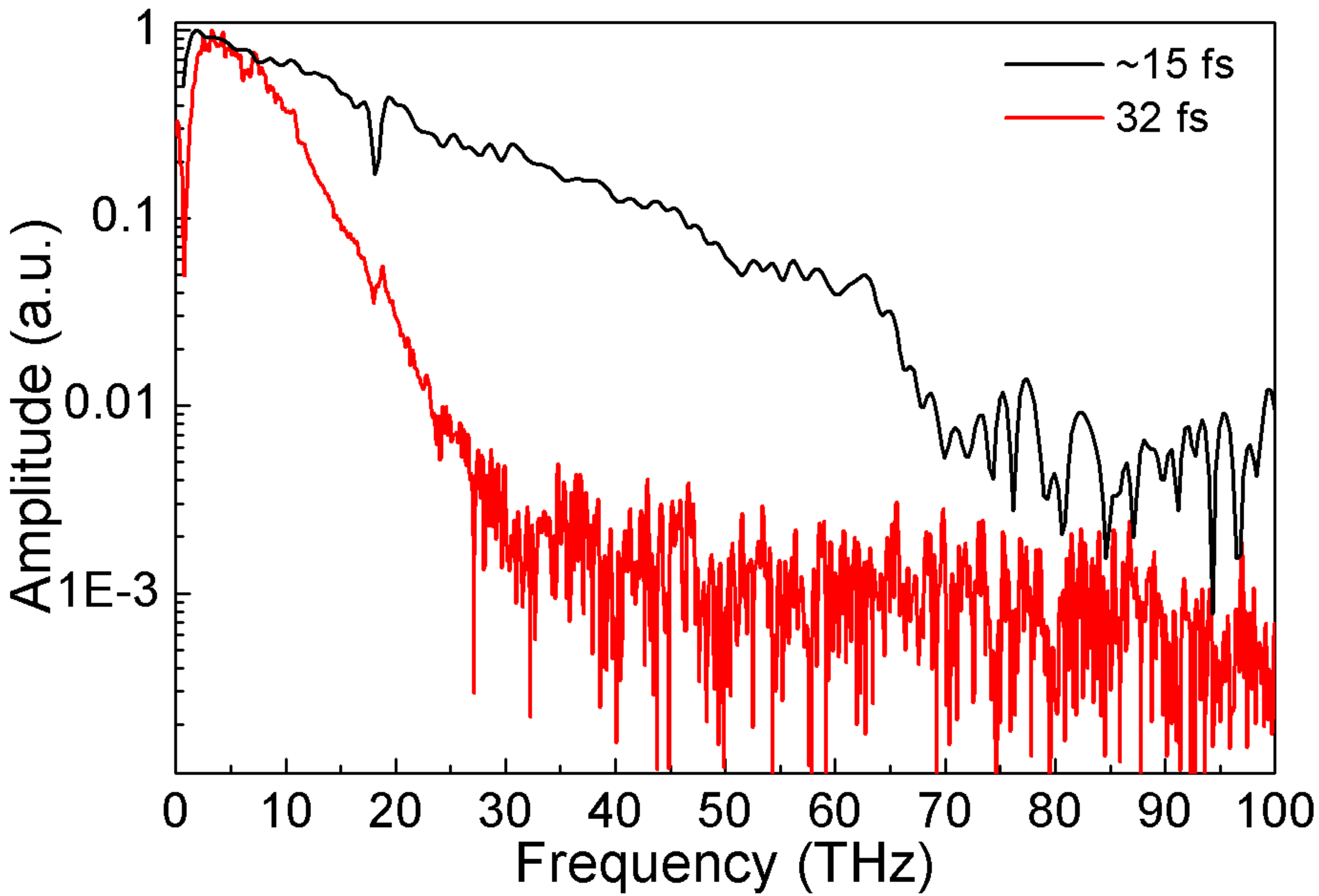
J. Dai, et al, Unpublished

Hollow-Fiber Pulse Compressor

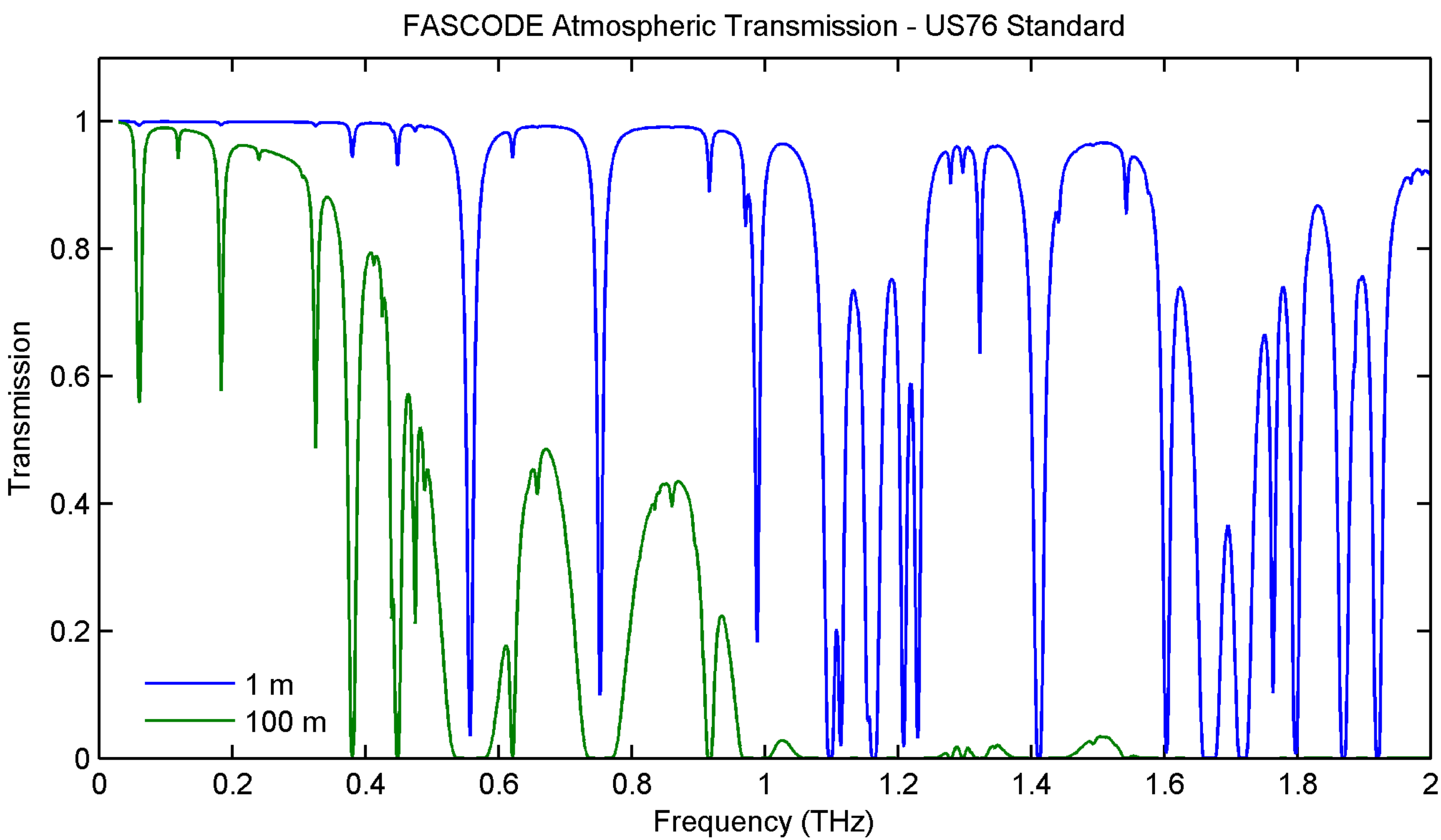
- Waveform and spectrum with hollow fiber pulse compressor



THz Spectrum with Sub-20 fs Pulses

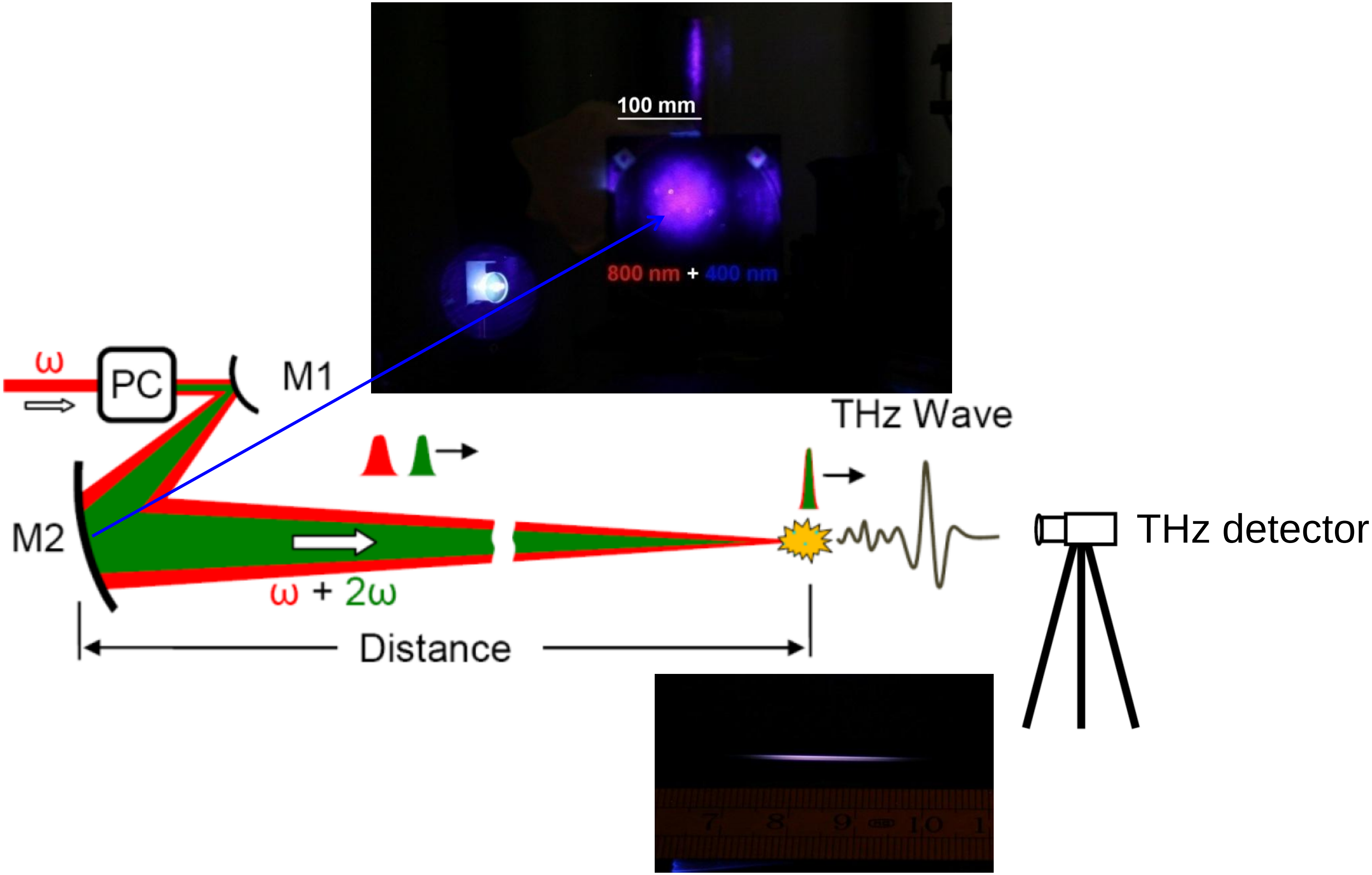


Atmospheric Absorption (Linear Scale)

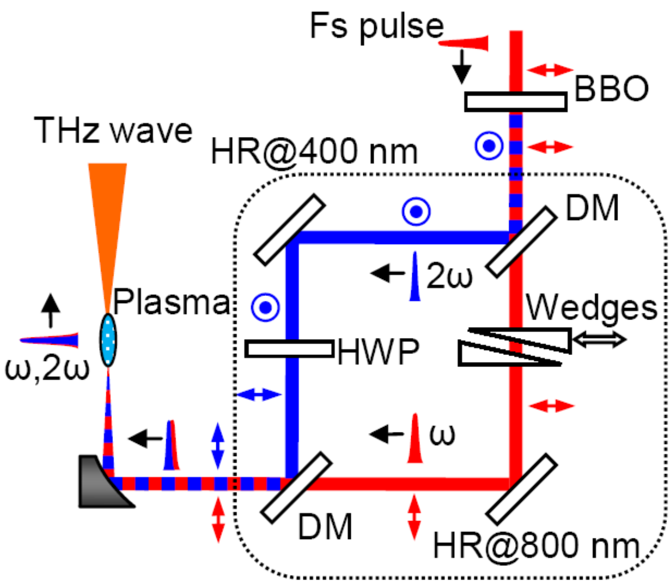


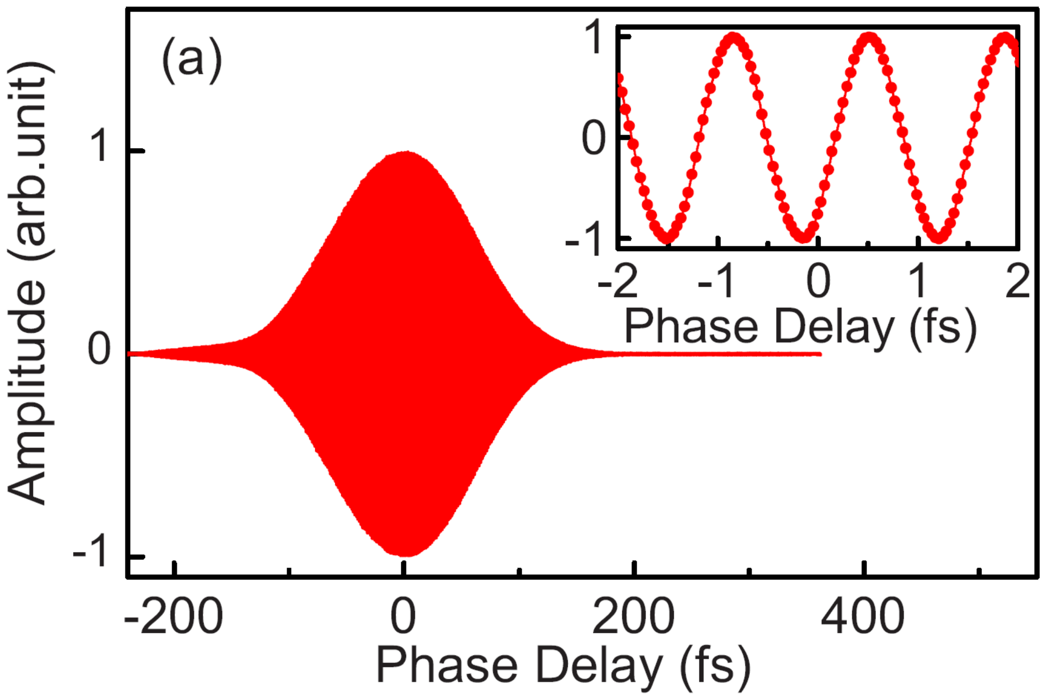
Courtesy from Doug McMakin at PNNL

Standoff THz Wave Generation



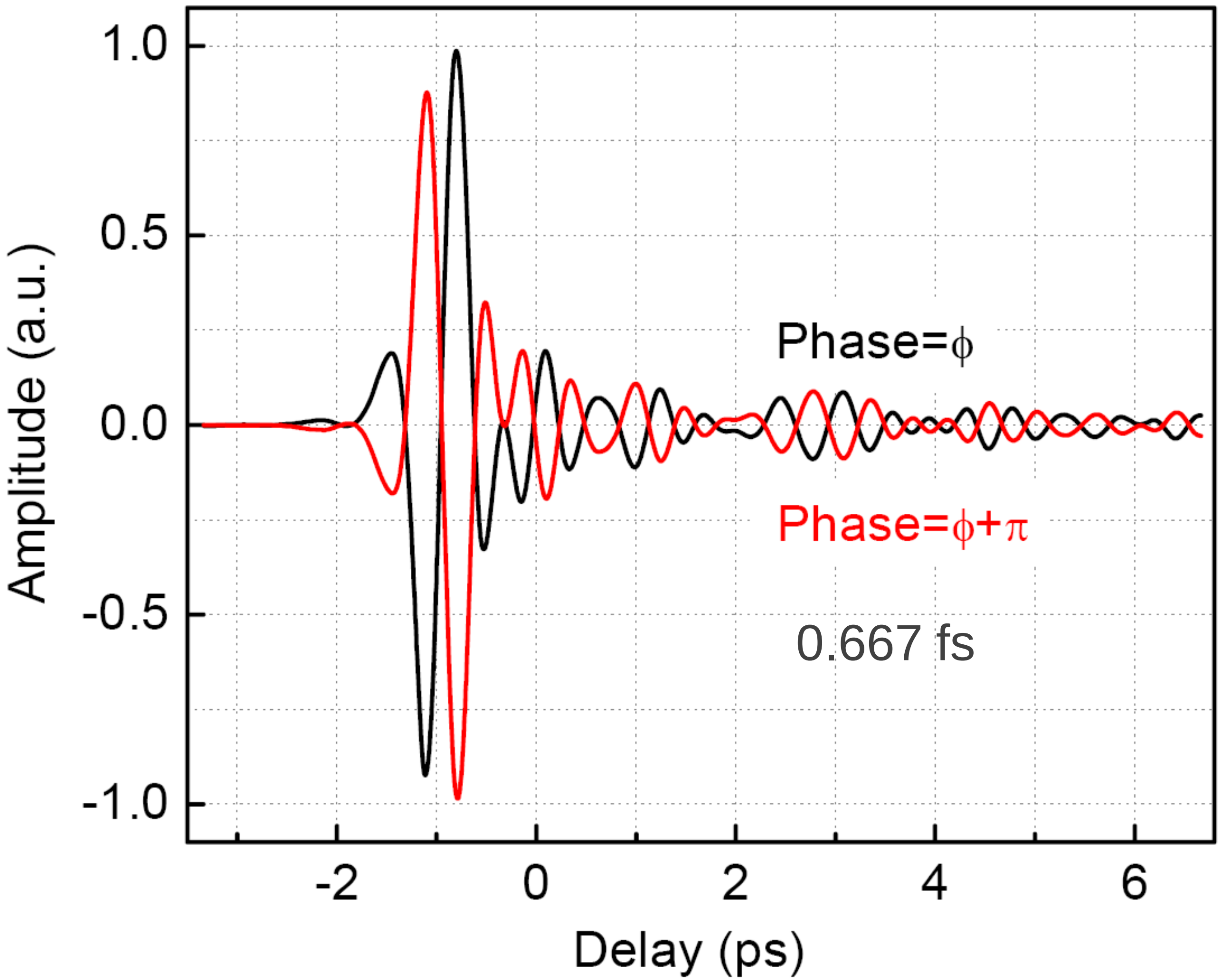
Coherent Control of THz Wave Generation



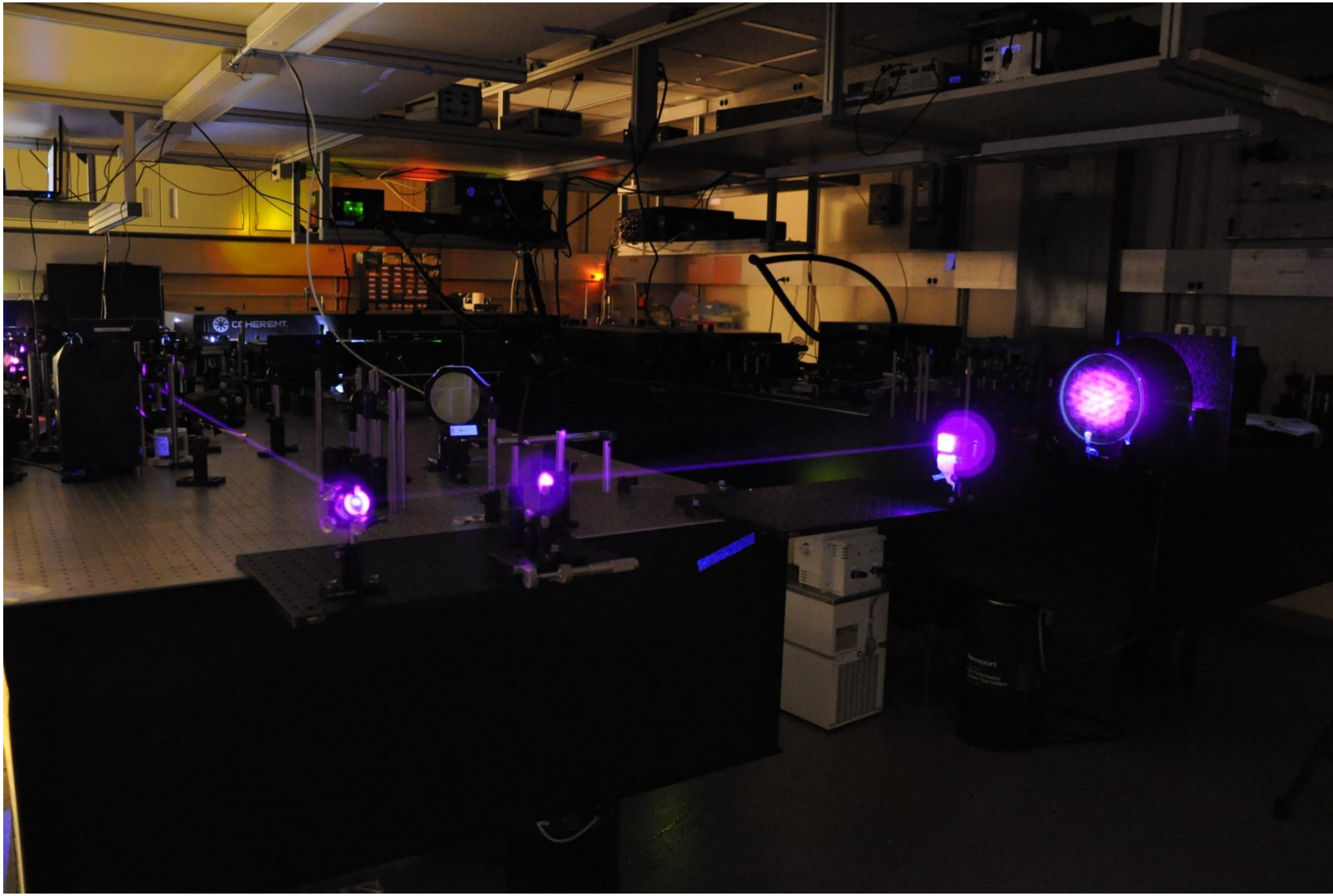


J. Dai and X.-C. Zhang, ***Appl. Phys. Lett. 94****, 021117 (2009)*

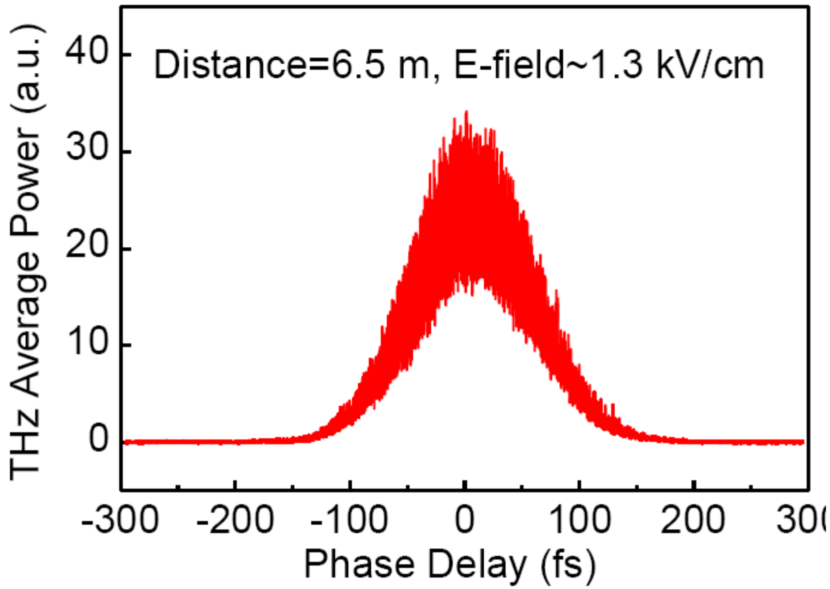
Flipped THz Waveforms

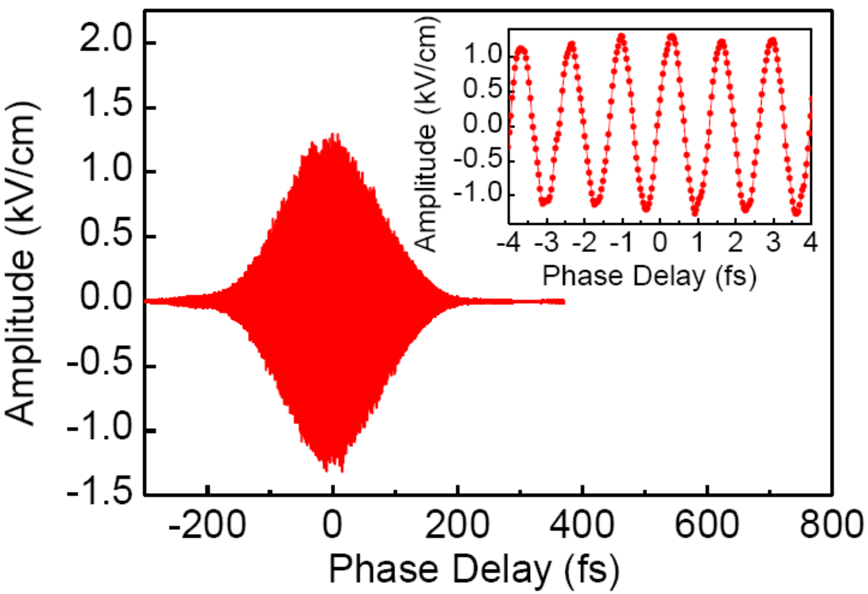


Standoff THz Generation with ~30 fs Laser Pulses

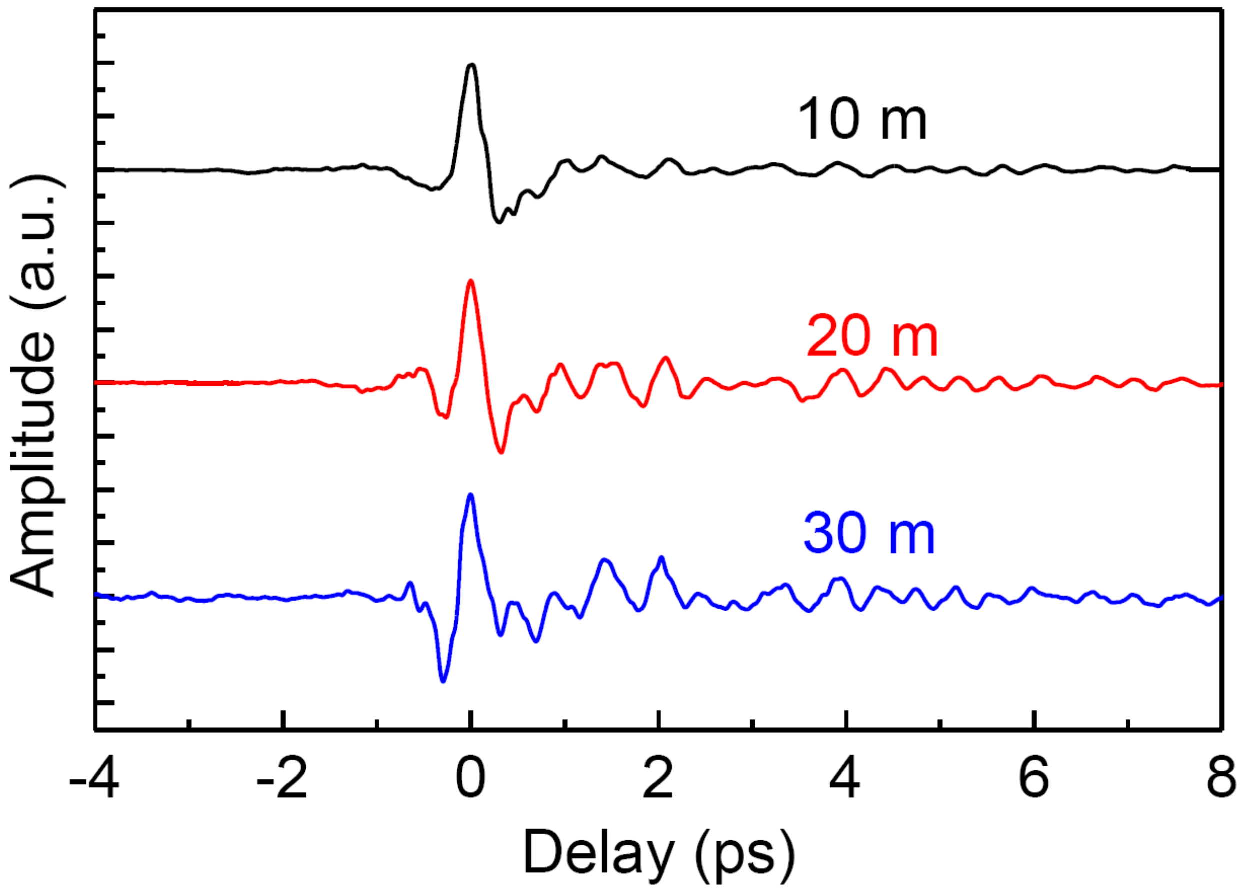


Phase Scans at 6.5 m



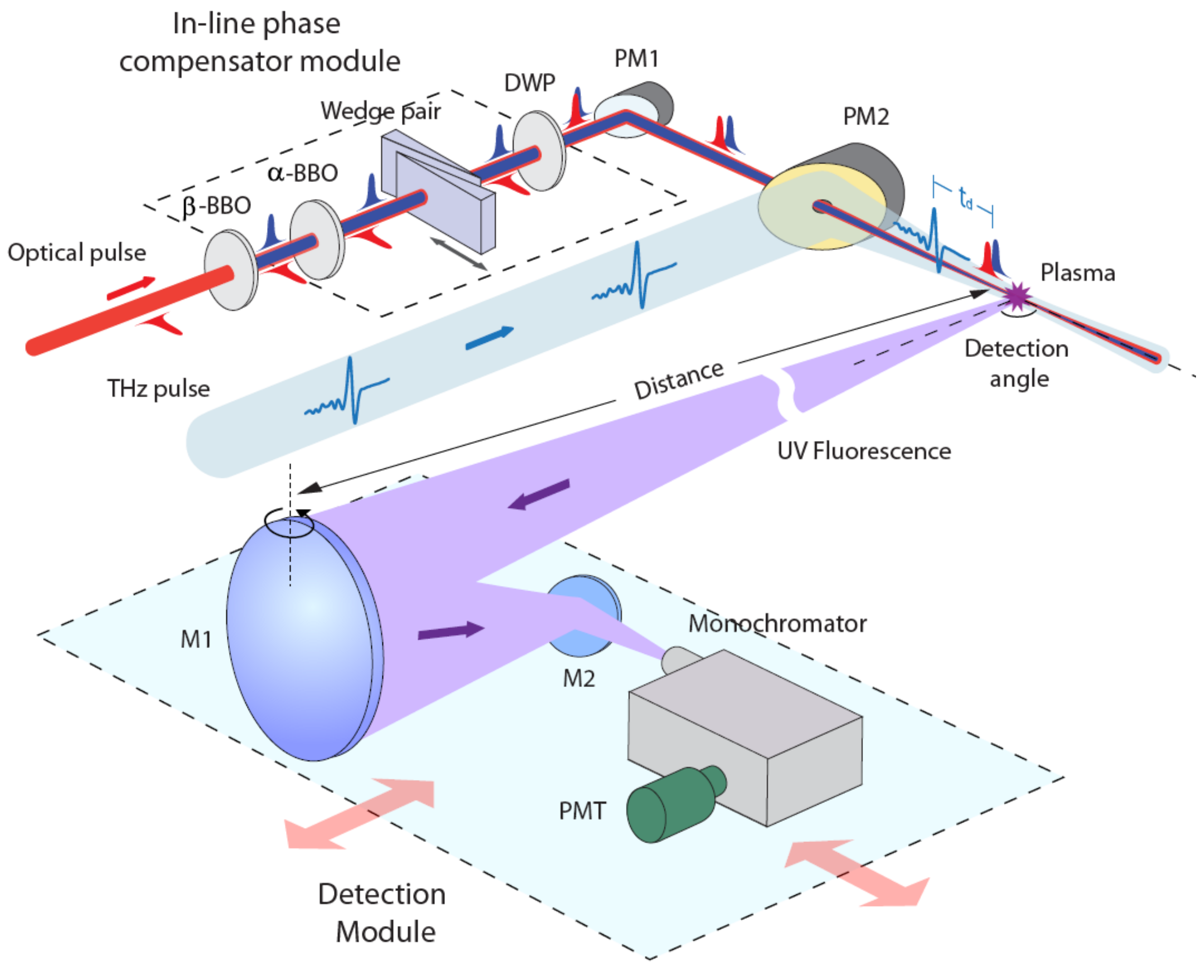


THz Wave Generation at 10 m, 20 m, and 30 m



Laser pulse: 4.4 mJ, ~30 fs

Remote THz Wave Sensing with Two-Color REEF

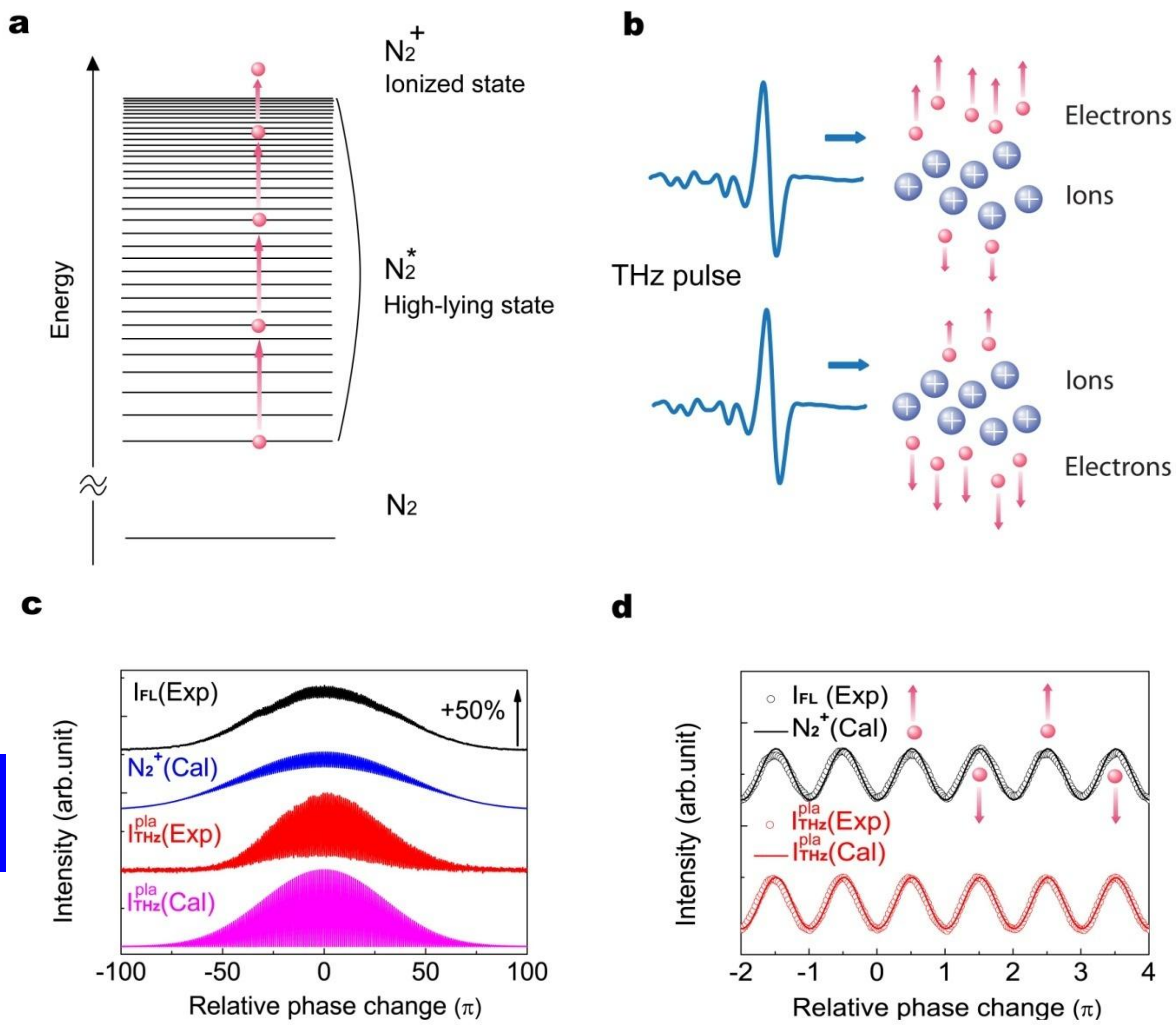


J. Liu, J. Dai, S.L. Chin, and X.-C. Zhang, ***Nature Photonics 4****, 627 (2010)*

THz-wave-assisted electron impact ionization

Collisional excitation

Fluorescence &THz emission

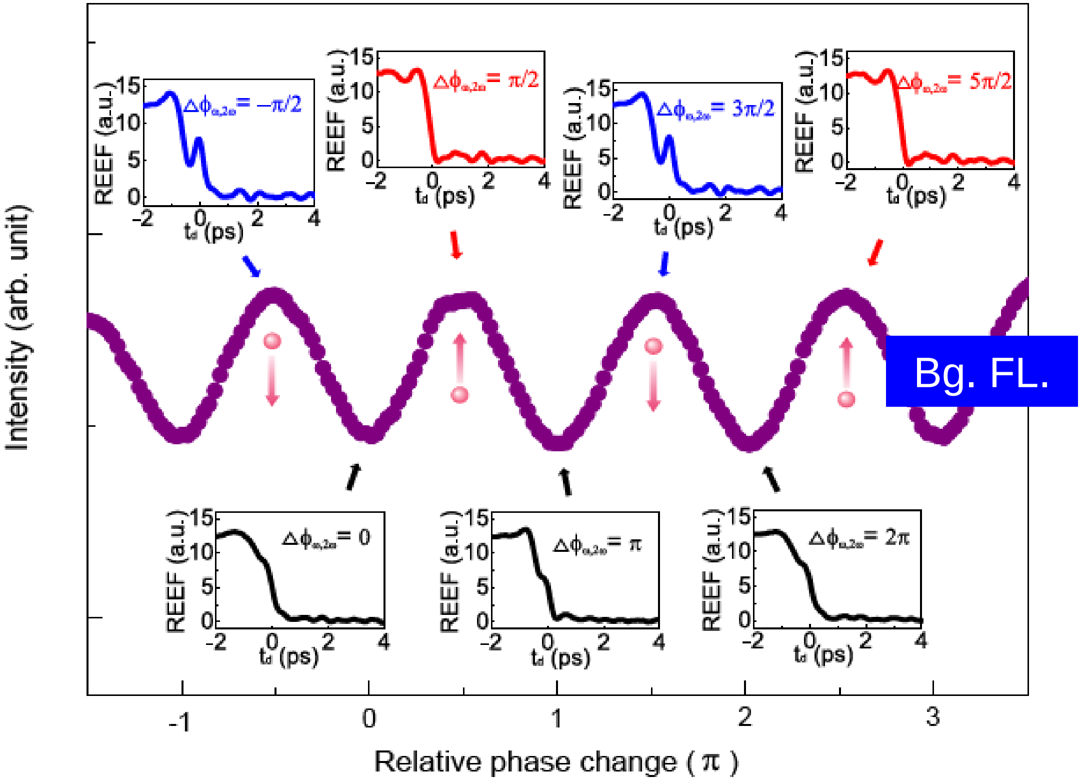


phase +π/2

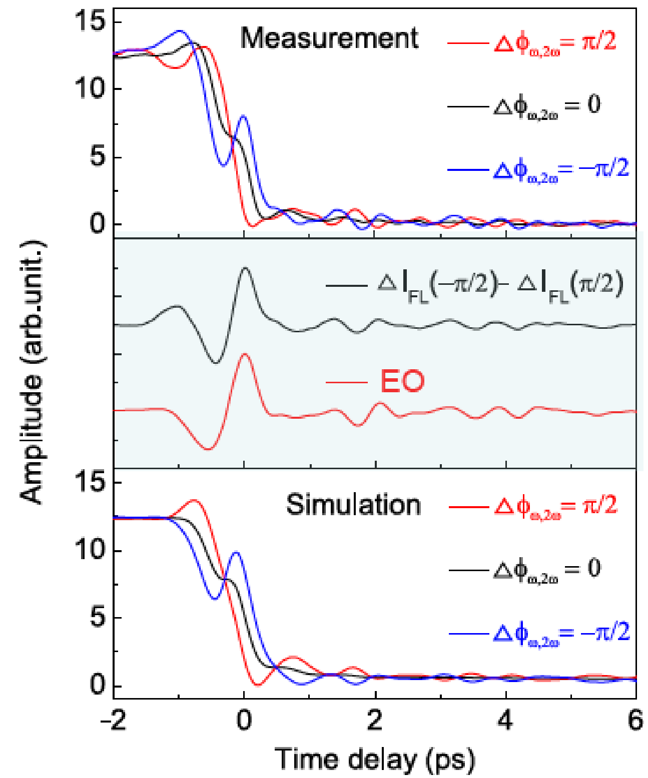
phase -π/2

Zoom in

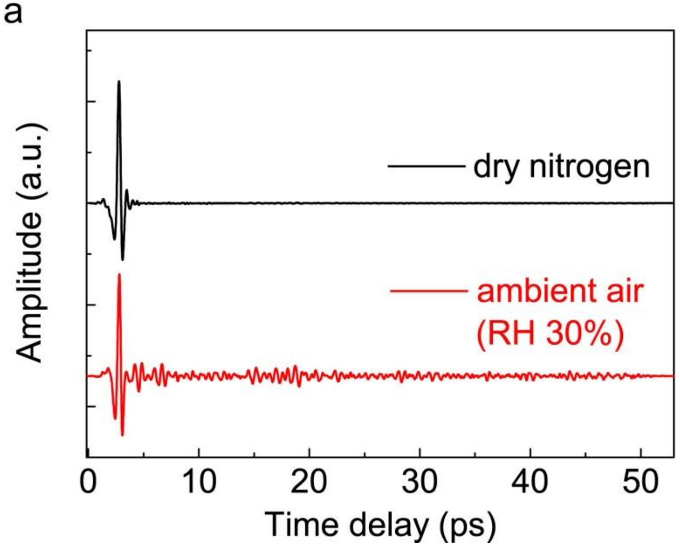
2-color phase dependence and coherent THz detection

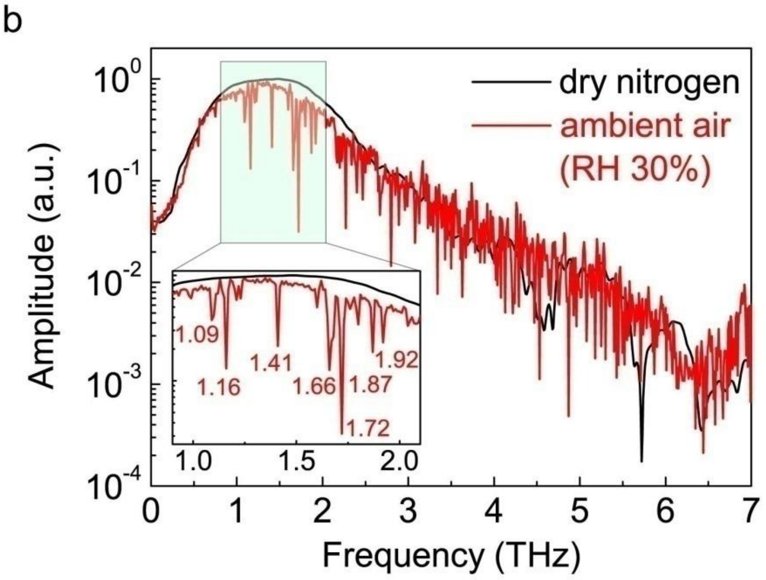


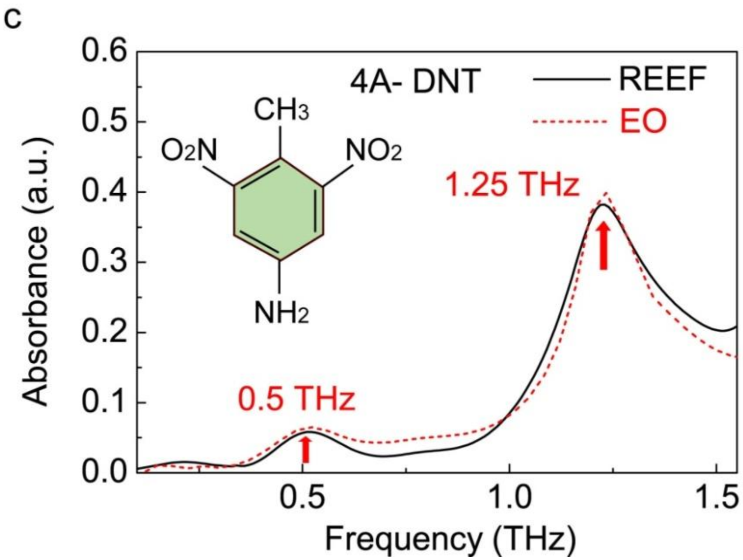
Coherent detection



Broadband THz wave sensing





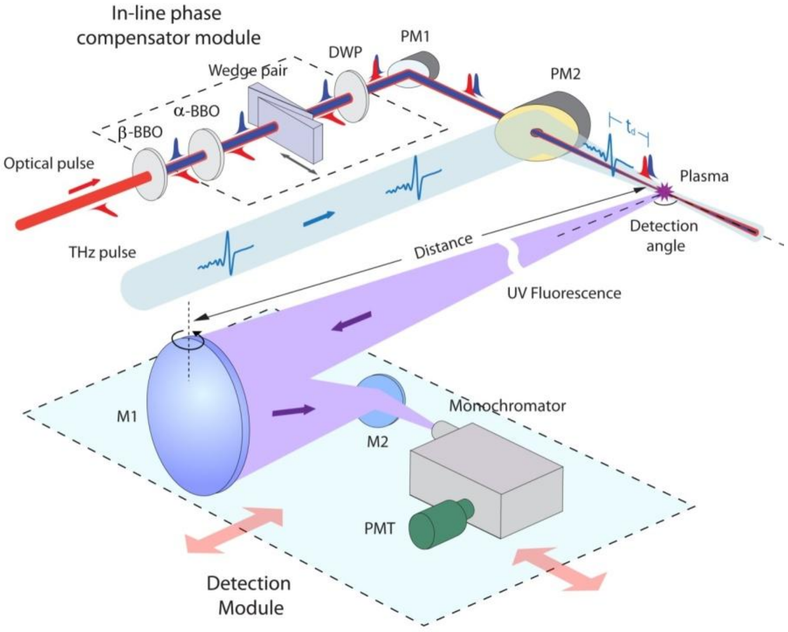


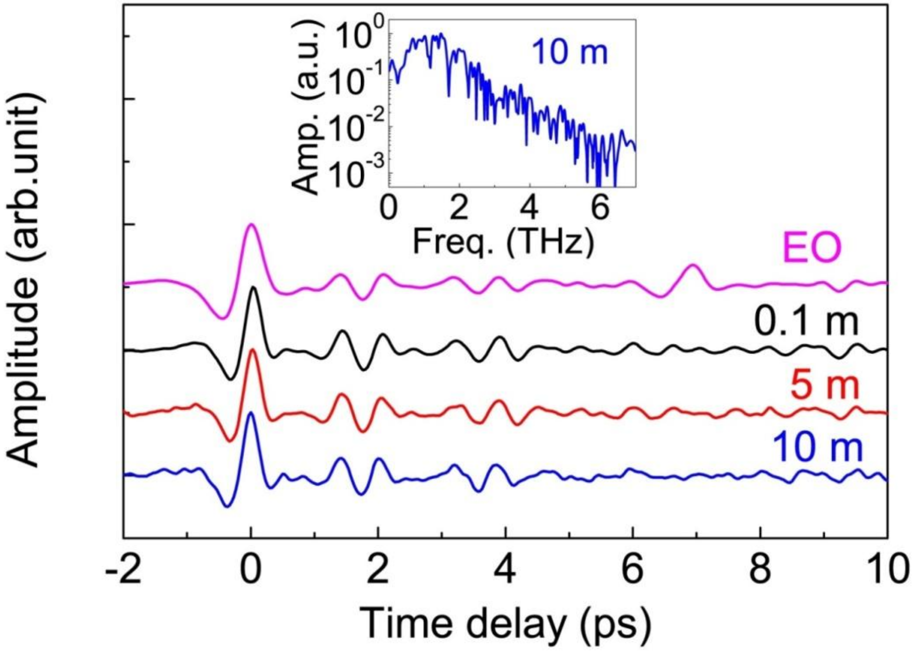
Broadband & high resolution
(Free of Fabry-Perot effect or phonon absorption)

Remote THz wave sensing (10 meter)

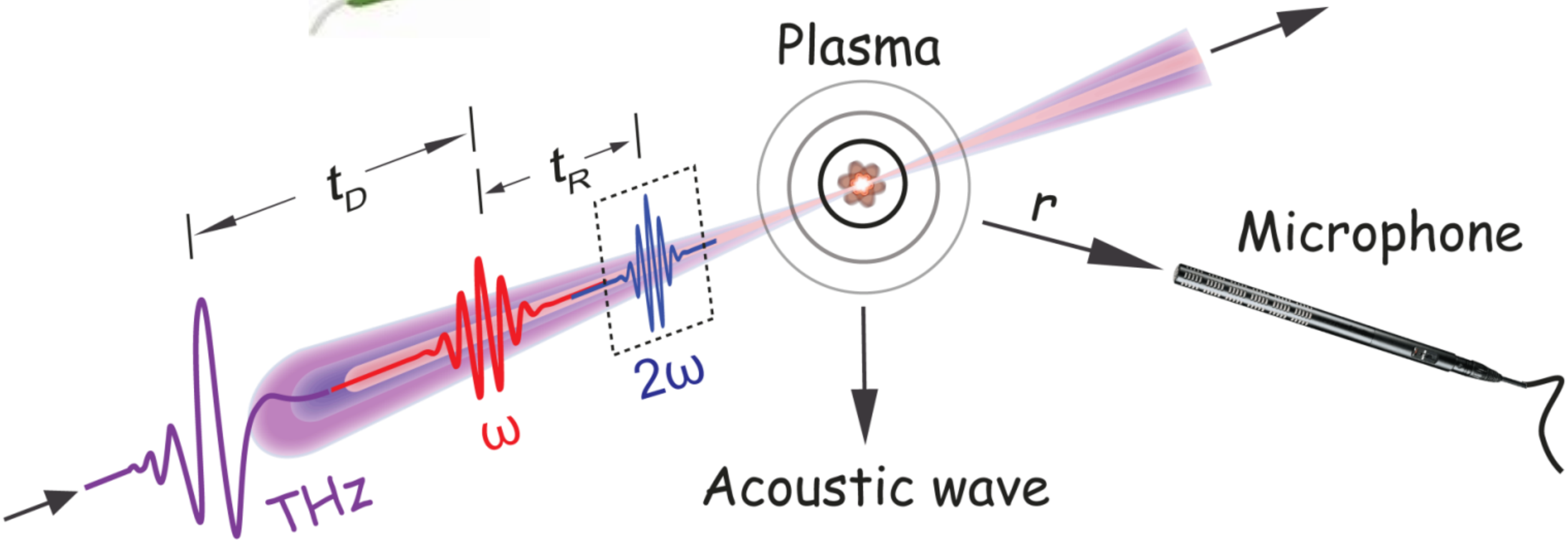
Advantages:
1) Minimal water vapor attenuation
2) Unlimited optical signal collection

THz time domain waveform by REEF and EO





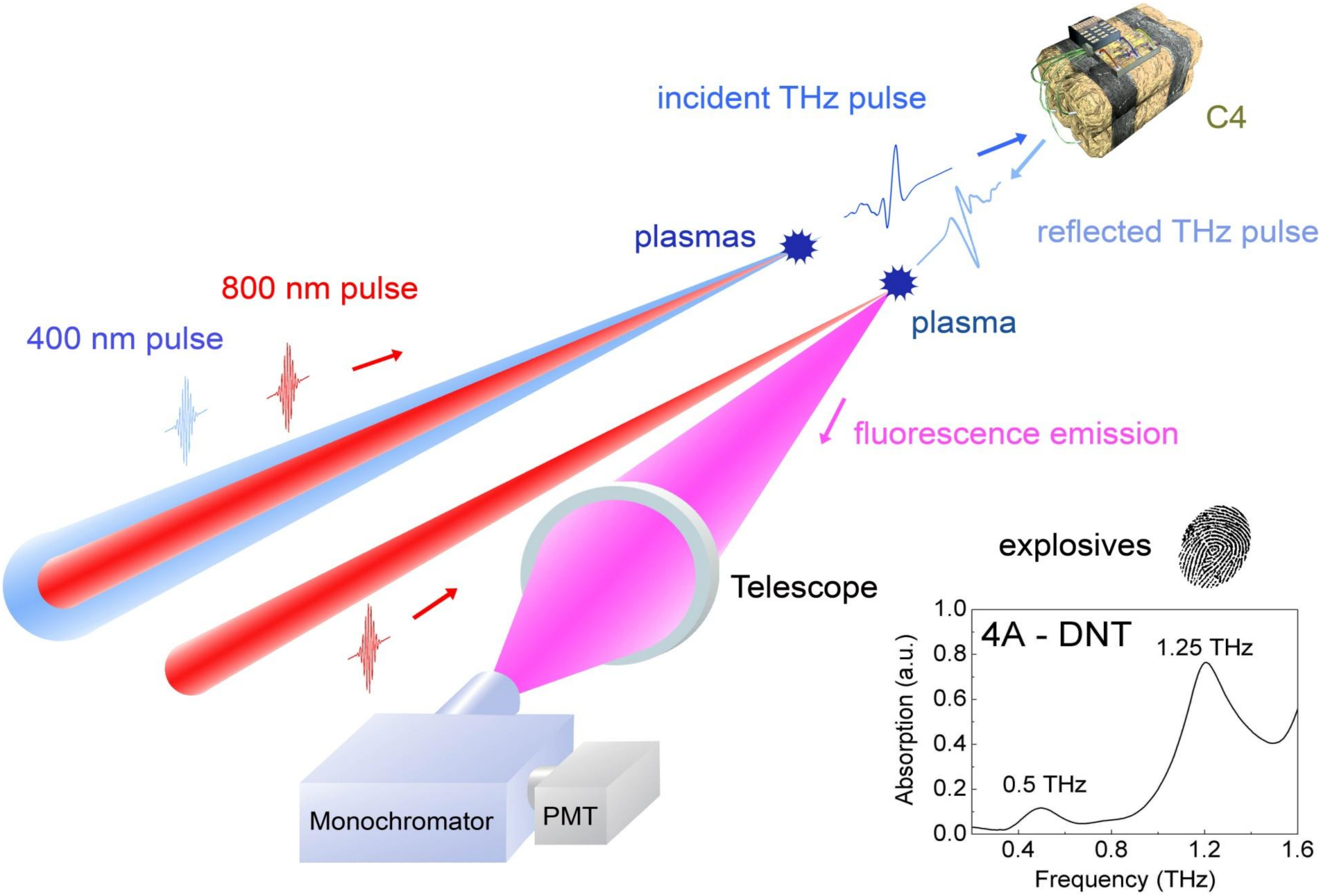
TEA 



Measured by a G.R.A.S. microphone

B. Clough and X.-C. Zhang, ***Optics Letters*** *35, 3544 (2010)*

Remote Sensing ?



Pros and Cons of THz Wave Air Photonics

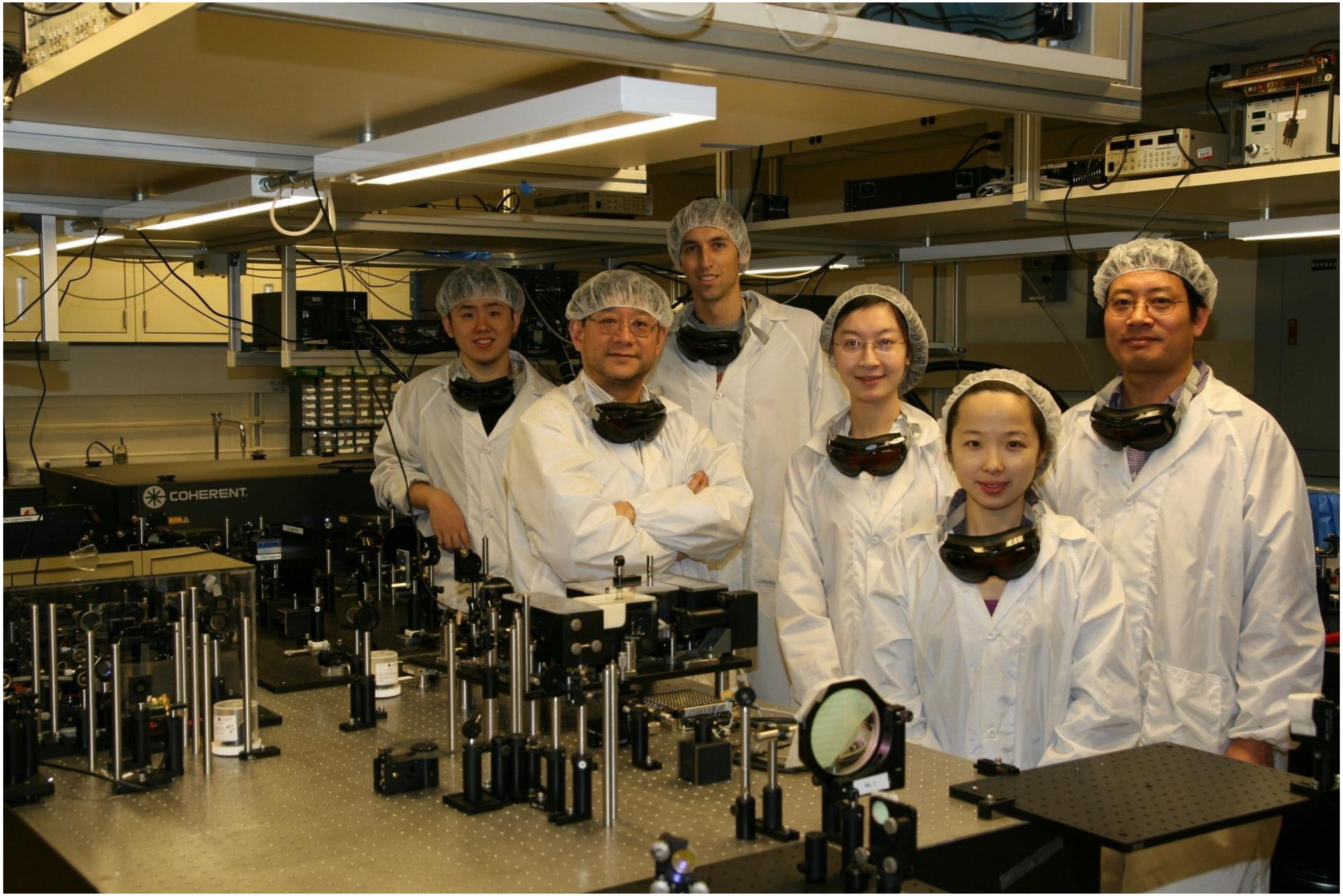
Pros

- ❑ High THz field:
  (a) >100 kV/cm (~100fs, 1-mJ laser pulses);
  (b) >1.5 MV/cm (~28fs, 2.7-mJ laser pulses) with ultra-broadband smooth spectrum
- ❑ Good THz beam profile and directionality
- ❑ No emitter damage issue
- ❑ Potential applications in remote THz wave sensing and nonlinear THz spectroscopy

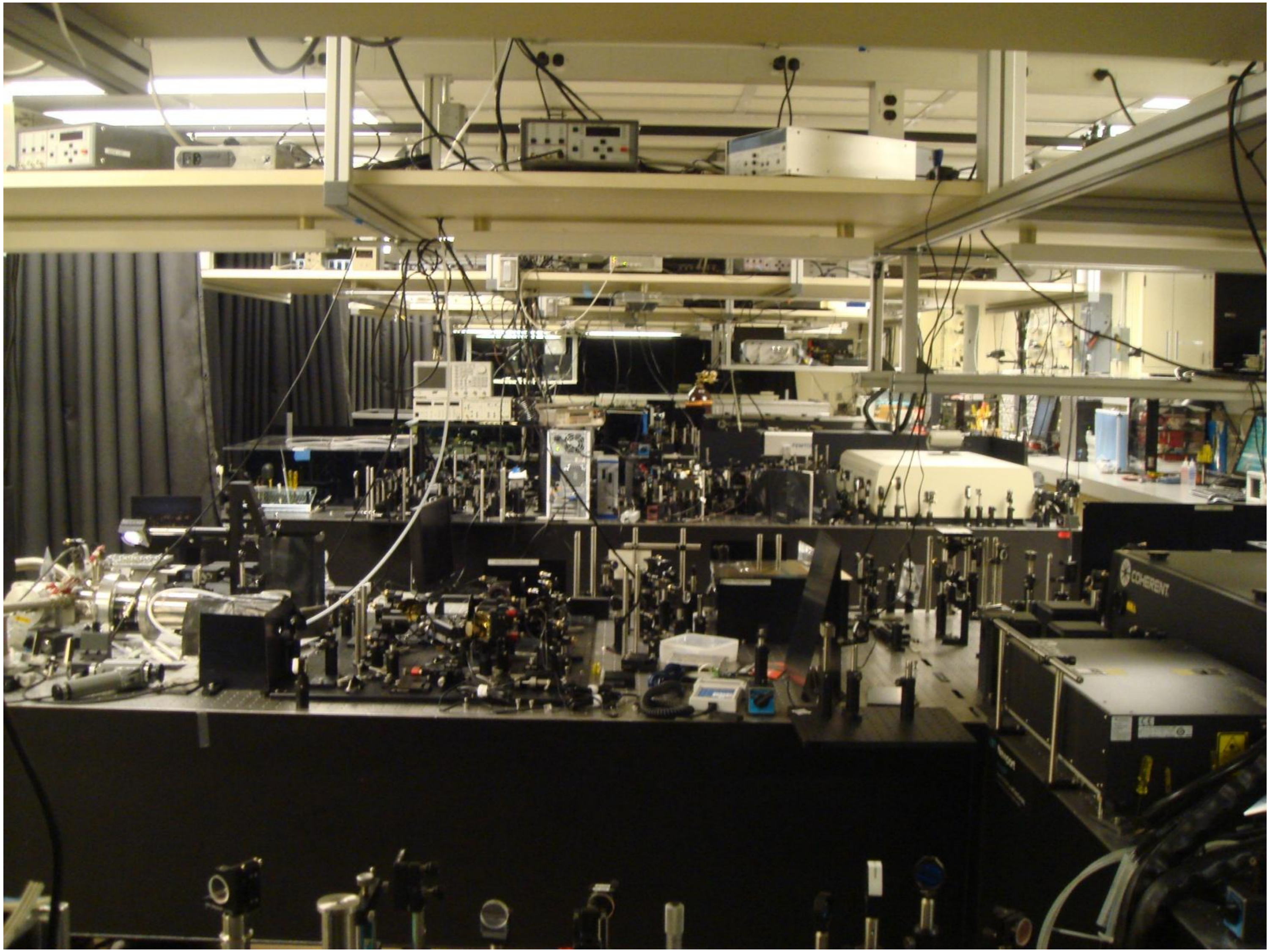
Cons

- ❑ Amplified laser (about mJ/pulse)
- ❑ Laser safety issue
- ❑ Third order nonlinearity (compared to solid THz source)

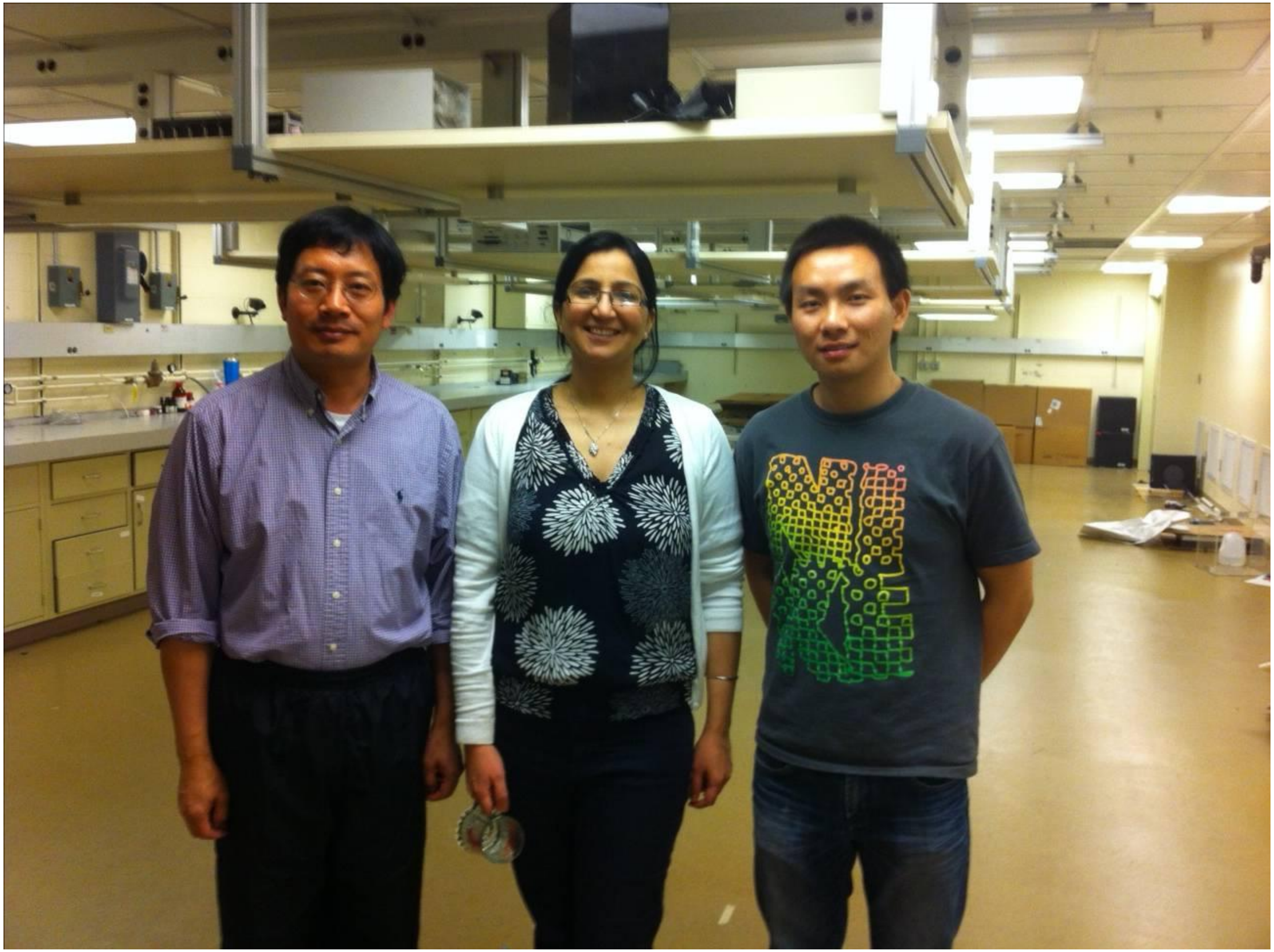
The THz Wave Air Photonics Team



W. M. Keck Laboratory at RPI, 2010



W. M. Keck Lab, February, 2012



New Labs in Goergen Hall at UR