THz/microwave emission from the 10 μm channel in air

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ONR MURI Kick-off meeting at UCLA, Oct 11-12, 2017

Institute for Research in Electronics & Applied Physics

Office of Naval Research
ONR
Science & Technology

physics
University of Maryland

Project goals:

- ❑ Study of THz/microwave emission from 10 μm filamentation:
  - Investigate THz/microwave generation mechanisms (single-color, two-color, 10.3 μm + 10.6 μm mixing schemes)
  - High-power THz/microwave generation
- ❑ Development of THz/microwave detection schemes:
  - THz/microwave characterization (energy, spectrum, polarization,…)
  - Single-shot THz/microwave spectroscopy with a femtosecond laser
- ❑ Characterization of CO_2 laser produced air filaments:
  - THz/microwave radiation spectral analysis
  - Plasma density measurement with a B-dot probe
  - Time-resolved THz spectroscopy with a femtosecond laser

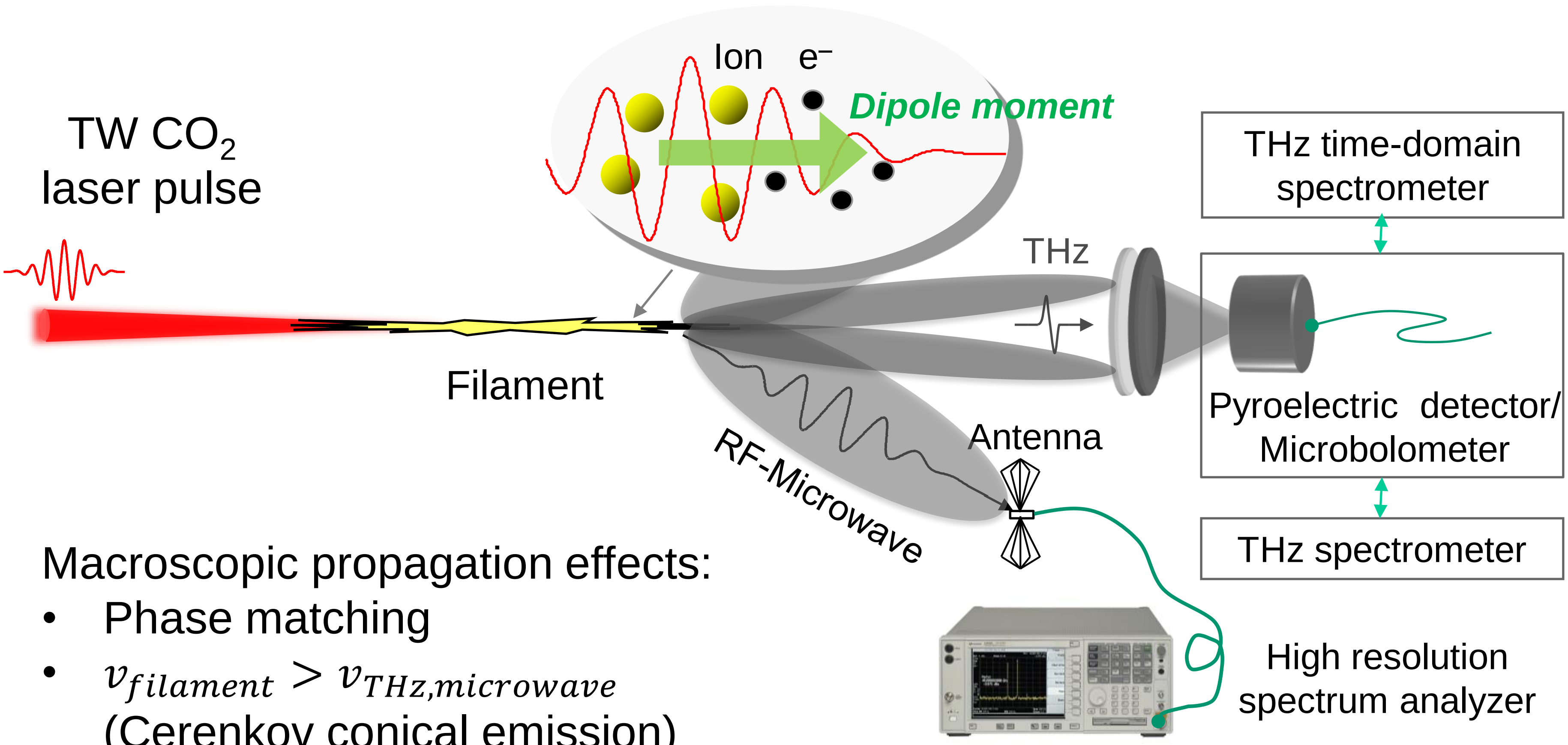
THz/Microwave generation:

Single-color filamentation

THz/microwave emission from filamentation

Microscopic effects:

- Fast electron current by the ponderomotive force ($\propto\lambda^2$, THz emission)
- Slow neutralizing current (microwave/rf emission)

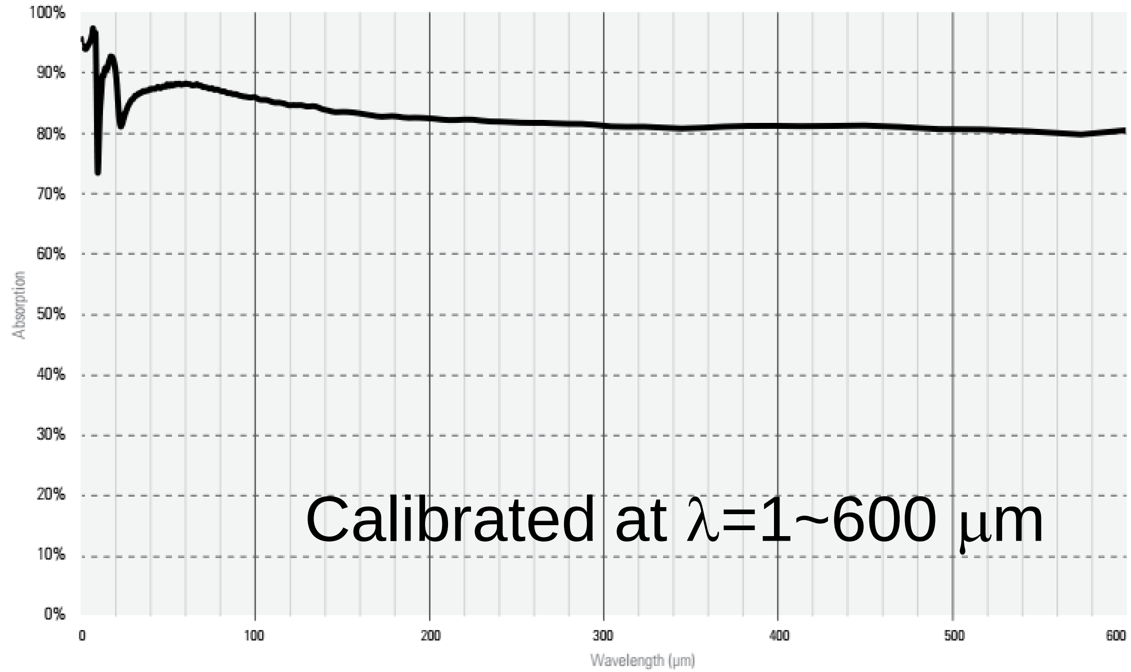


Macroscopic propagation effects:

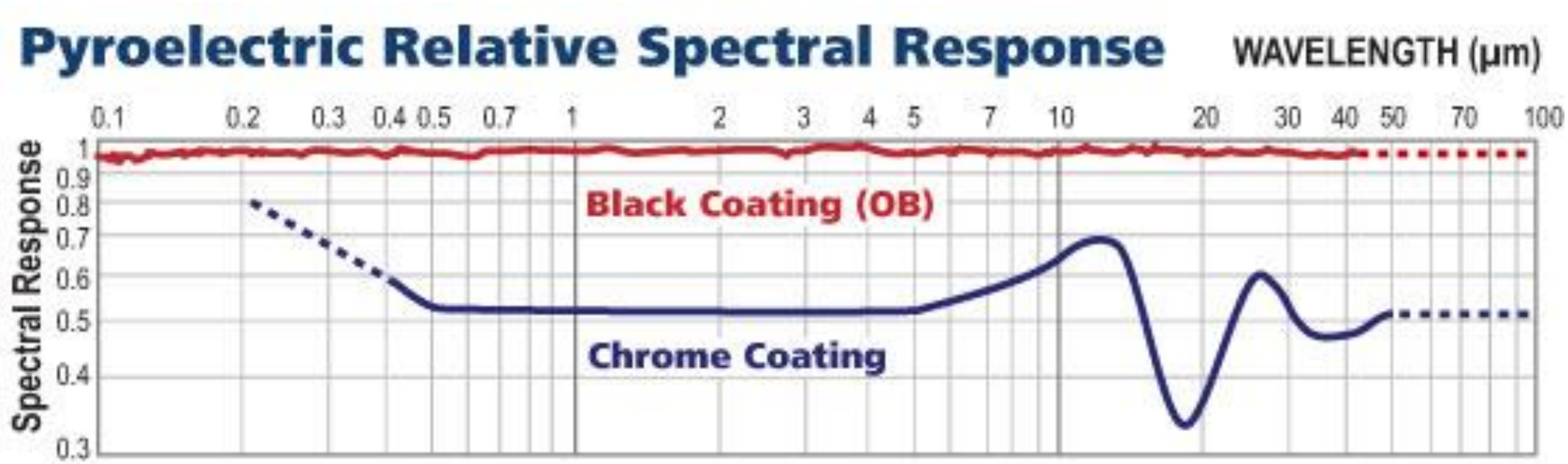
- Phase matching
- $v_{filament} > v_{THz,microwave}$ (Cerenkov conical emission)

Pyroelectric detectors

Absorption vs. wavelength



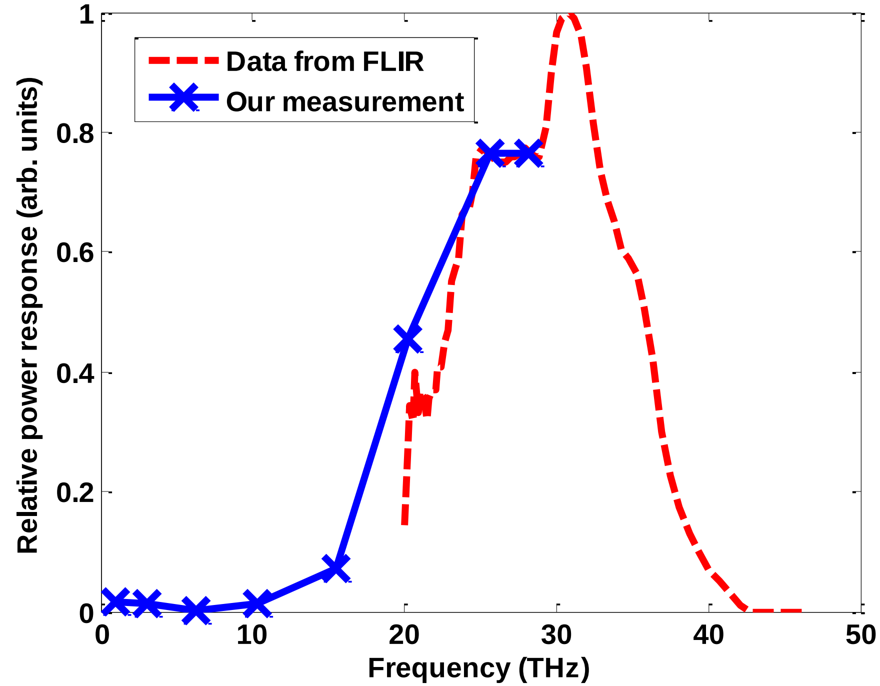
Calibrated at λ=1~600 μm

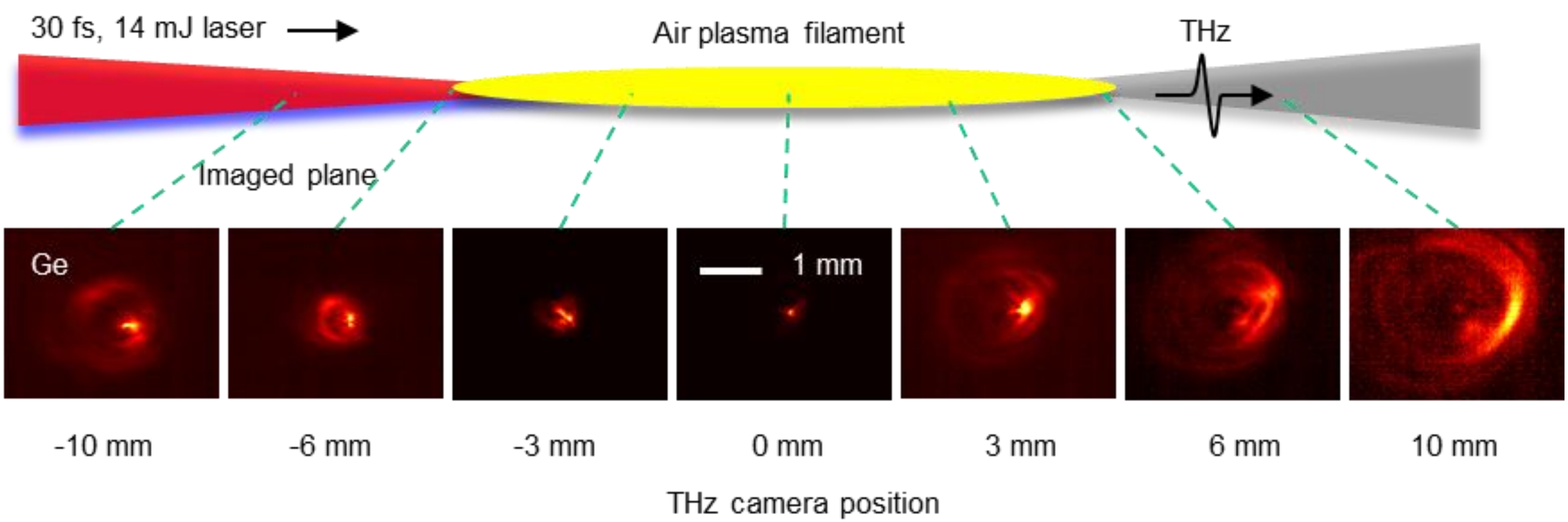


Microbolometers

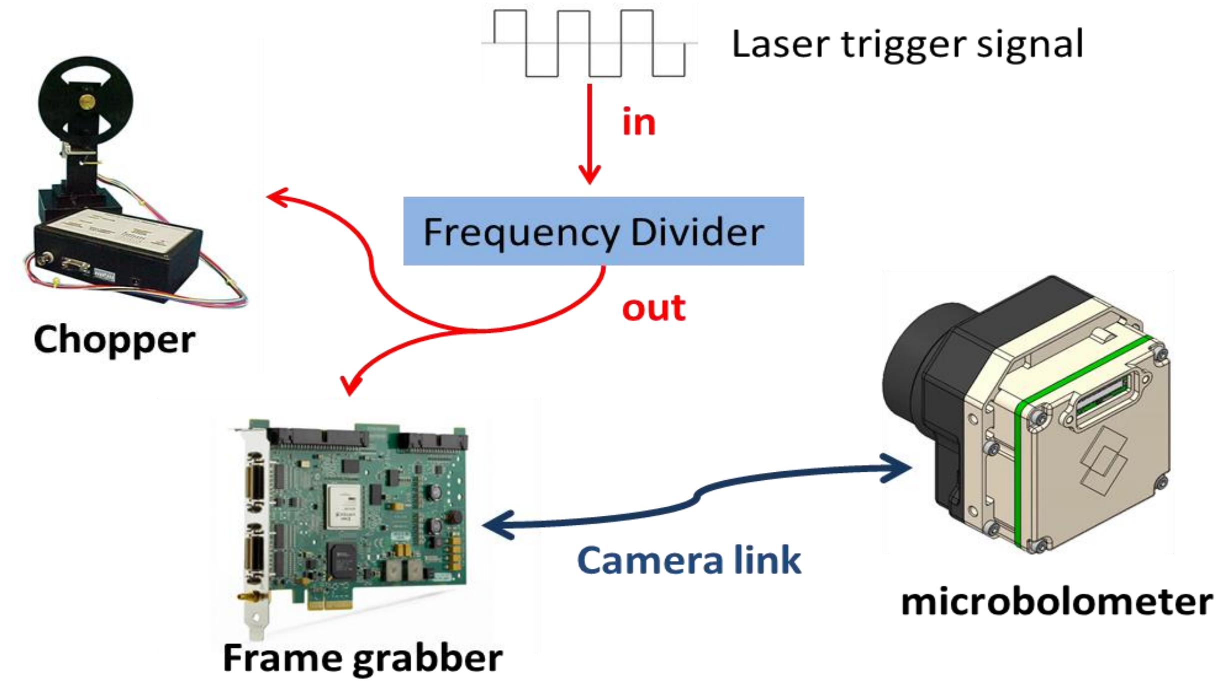
Uncooled microbolometer

Spectral response

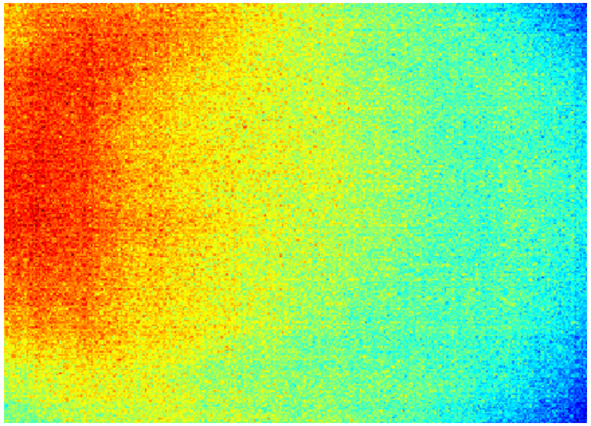




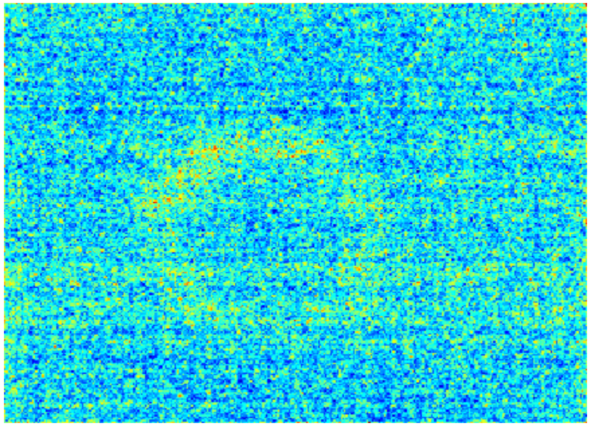
Lock-in imaging with microbolometers



Without Lock-in

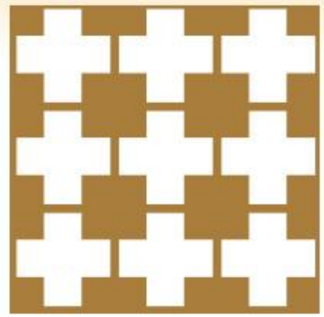


With Lock-in

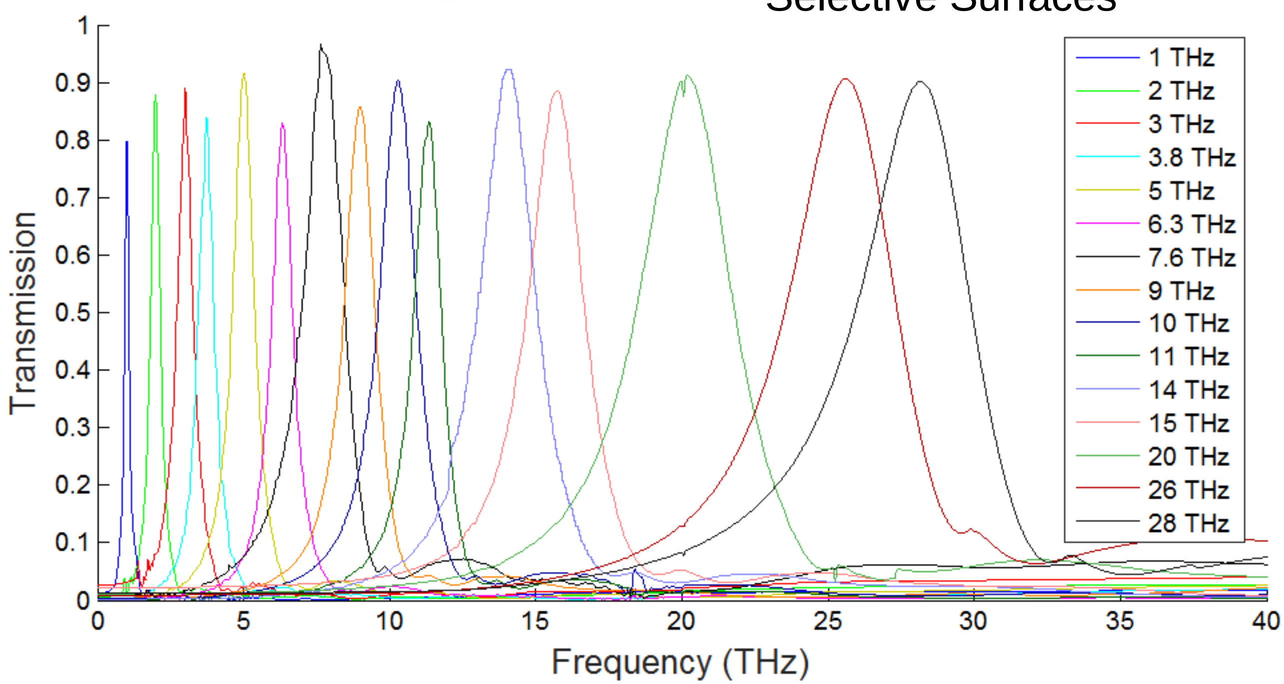


THz bandpass filters and polarizers

Bandpass THz filters



Gold-Mesh Frequency-Selective Surfaces

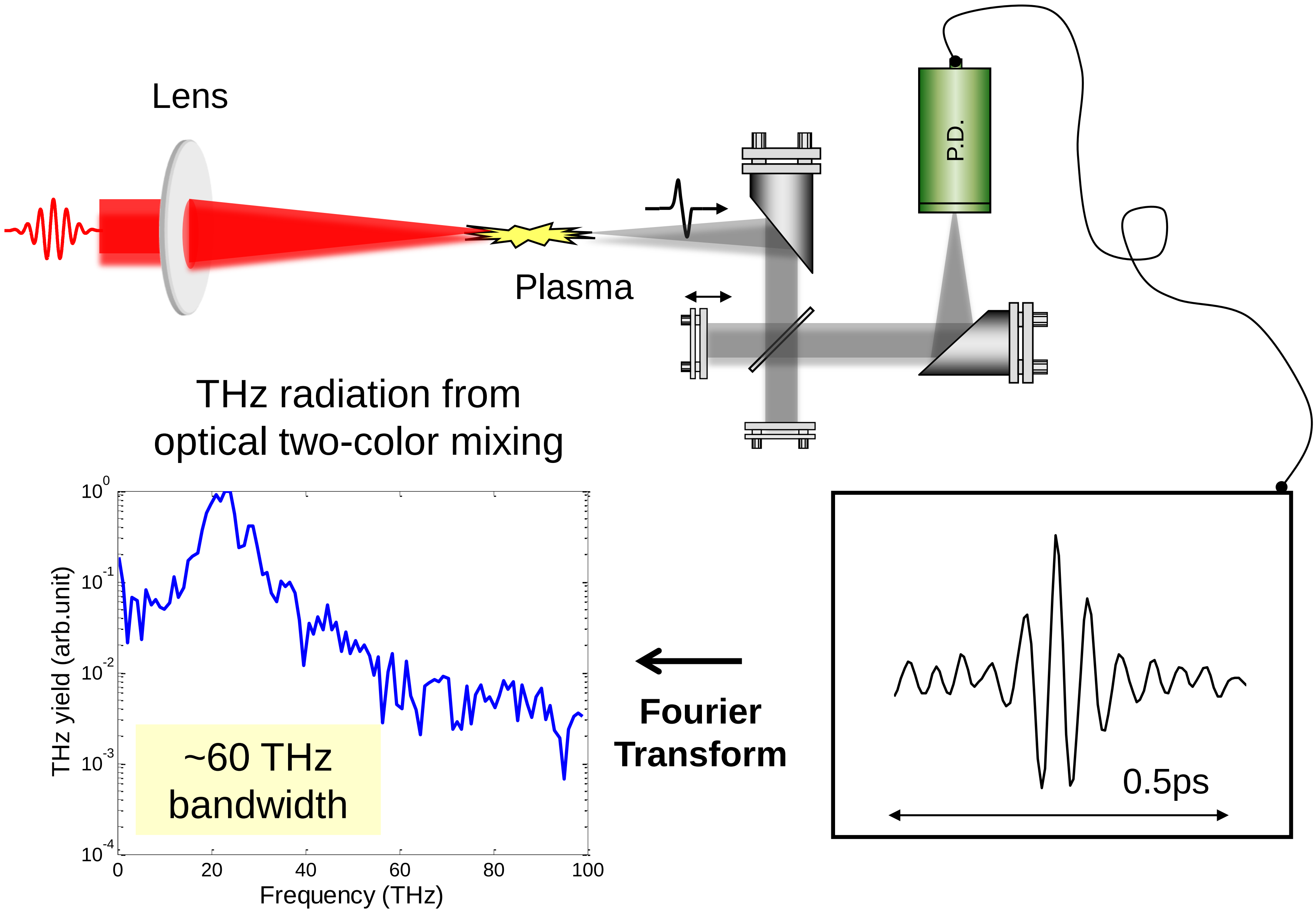


THz polarizers

Free Standing Wire Grid Polarizers

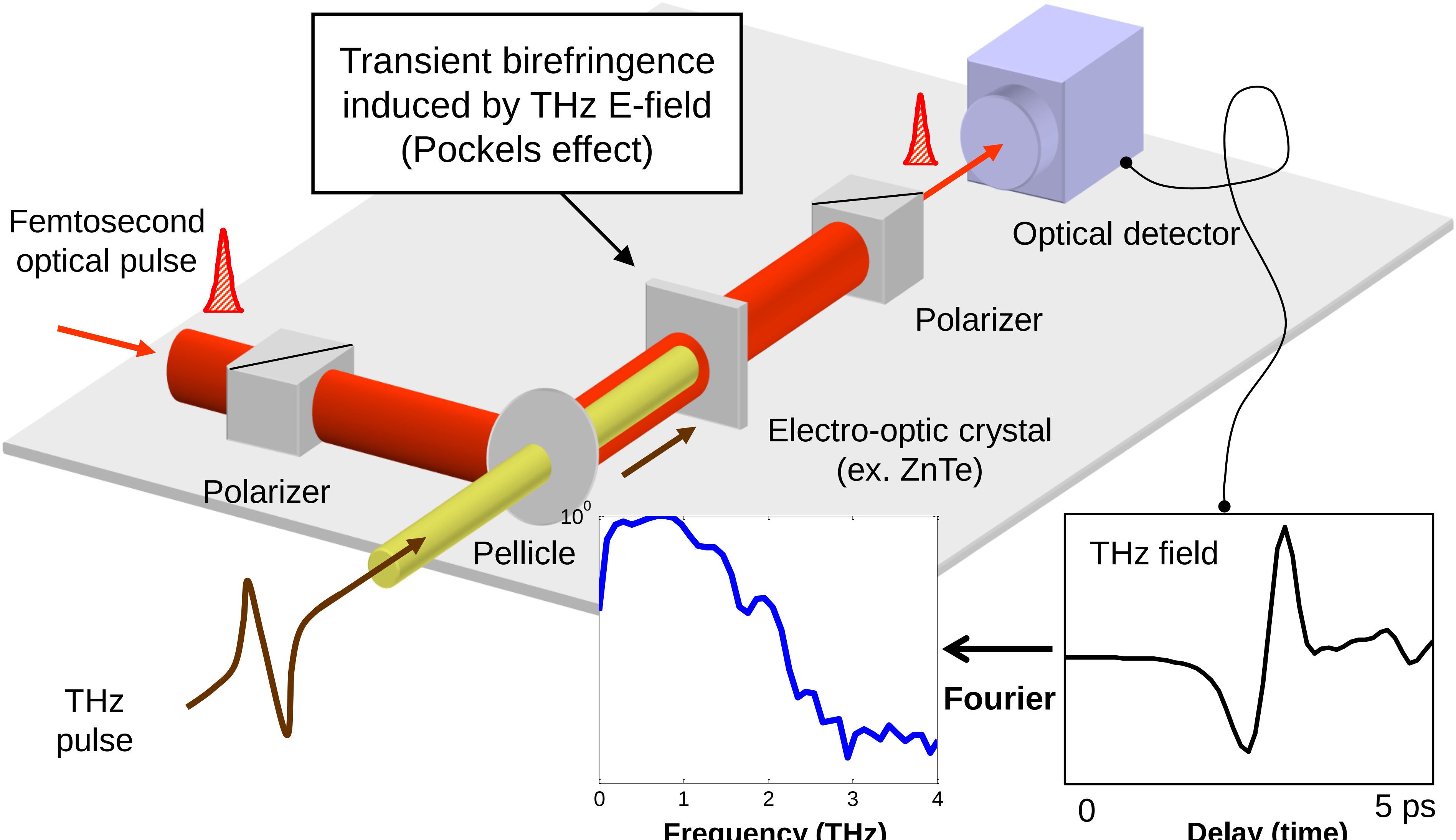
< 1 THz filters also available!

THz spectrum measurement via FTIR:

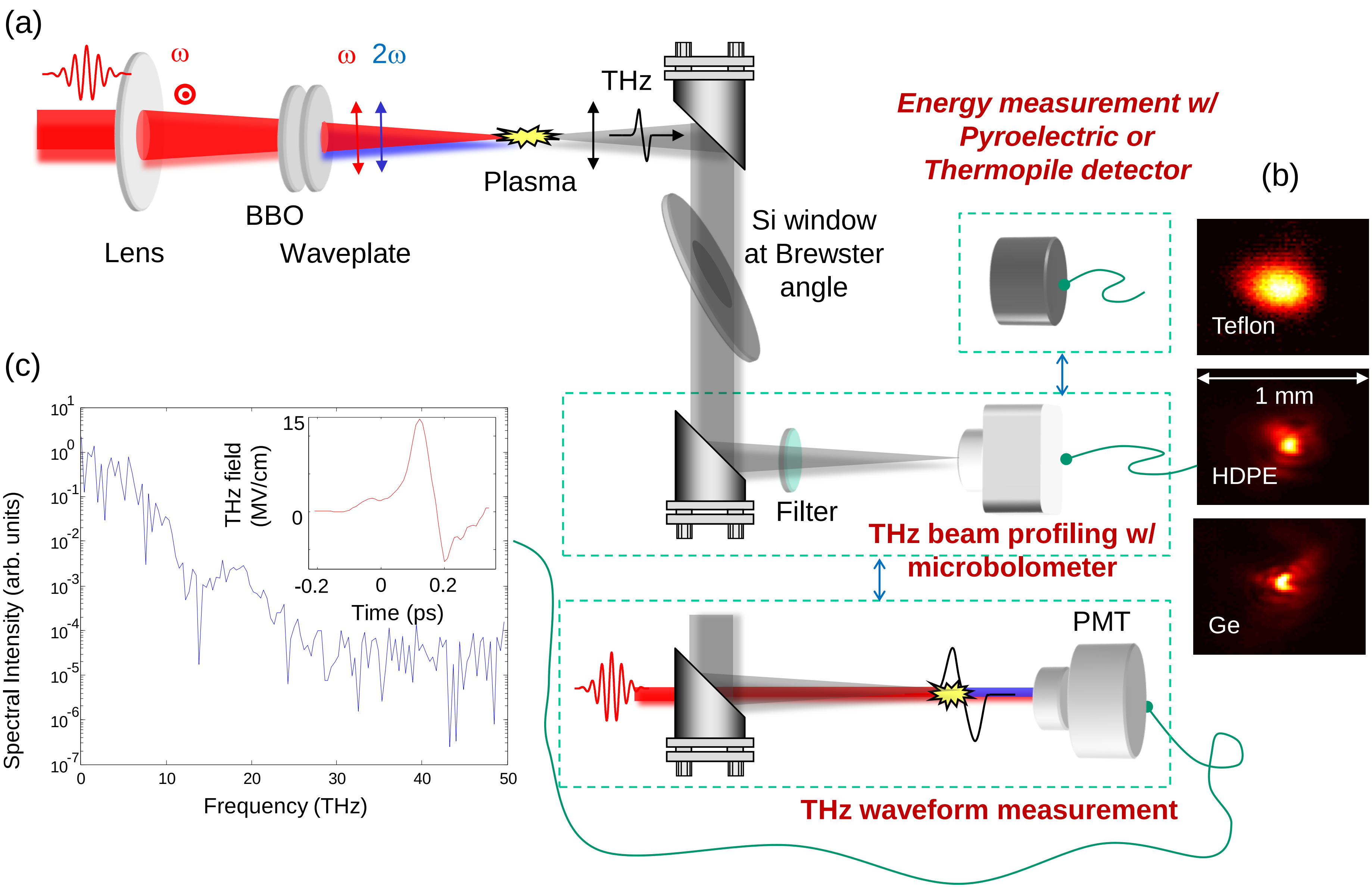


THz waveform measurement via **EOS**:

Electro-Optic Sampling

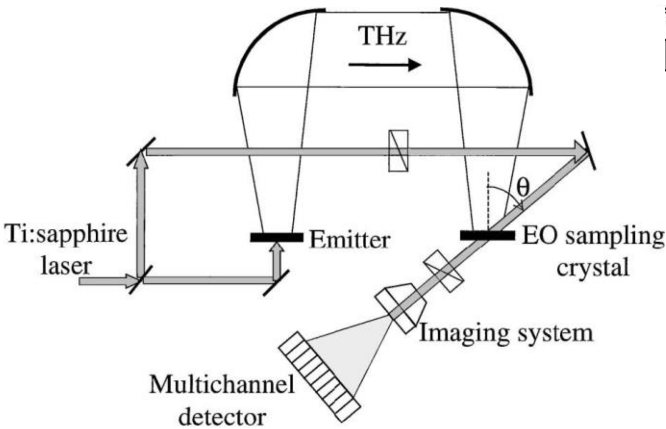


THz generation and detection:



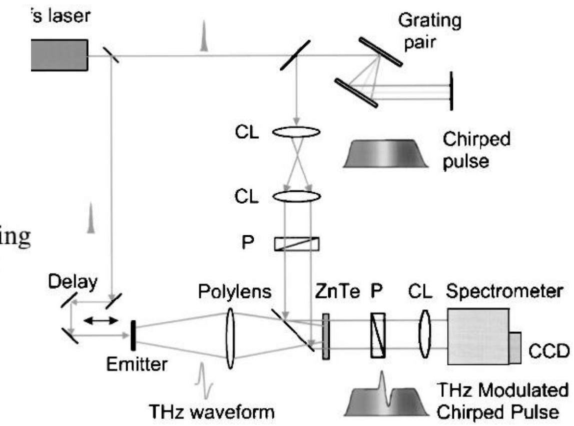
Single-shot THz waveform measurements

Spatial encoding



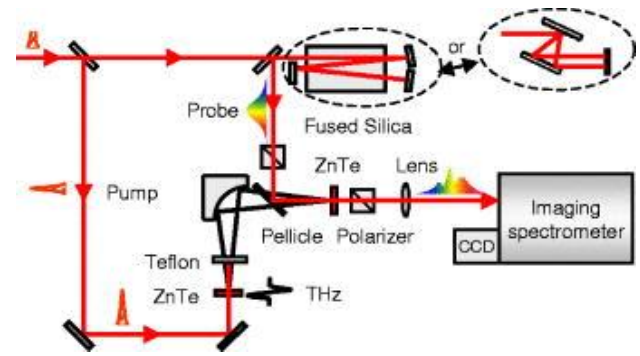
J. Shan *et al*., Opt. Lett. **25**, 426 (2000)

Spectral encoding



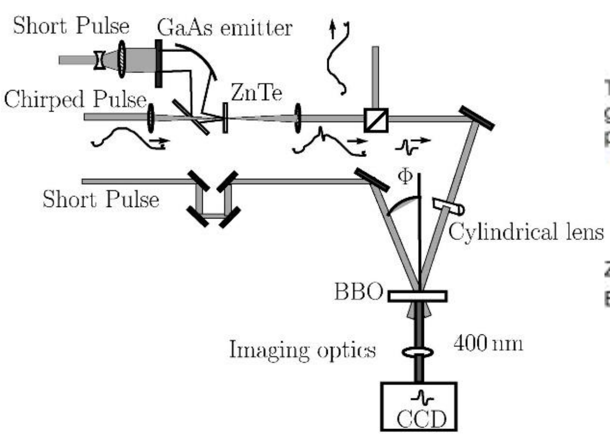
Z. Jiang *et al*., Opt. Lett. **23**, 1114 (1998)

Interferometric method



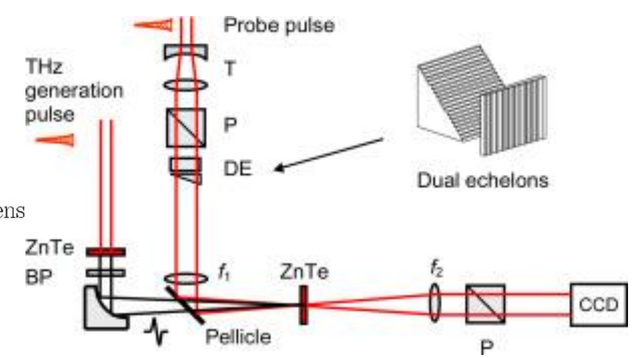
K. Y. Kim *et al*., APL **88**, 041123 (2006)

Noncollinear cross correlation



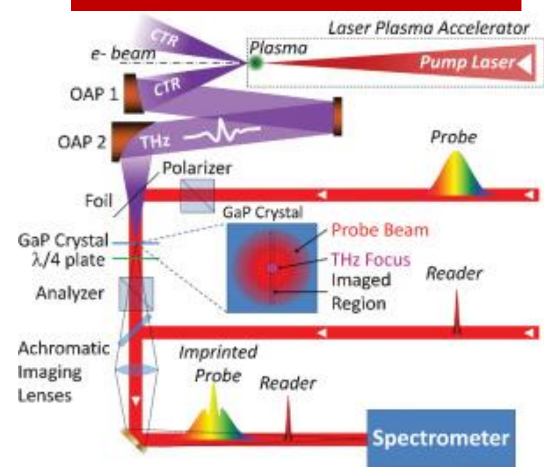
S. P. Jamison *et al*., Opt. Lett. **28**, 1710 (2003)

2D spatial encoding



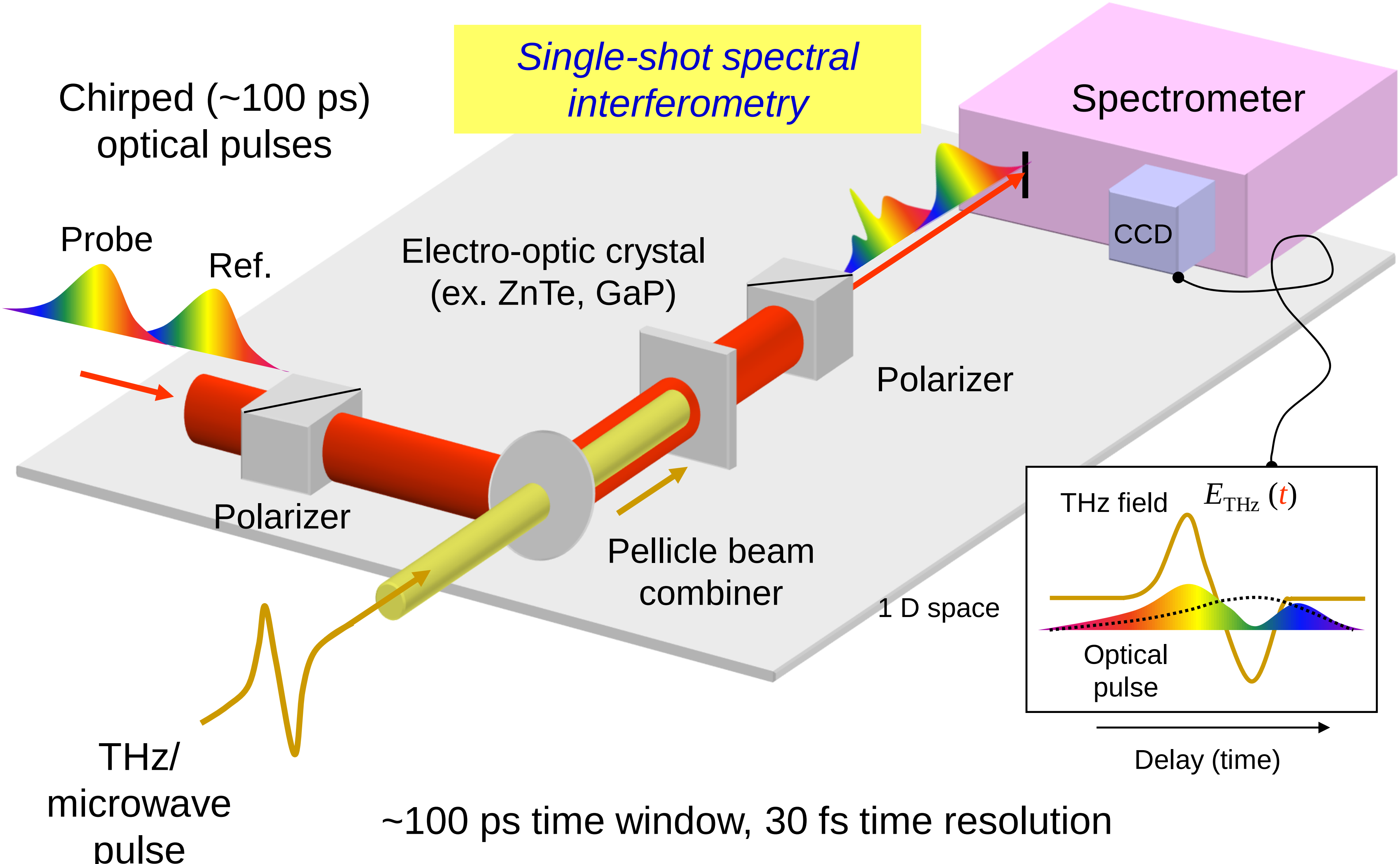
K. Y. Kim *et al*., Opt. Lett. **32**, 1968 (2007)

Cross correlation



N. H. Matlis *et al*., JOSA B **28**, 23 (2011)

High-resolution single-shot THz/μ wave spectrometer



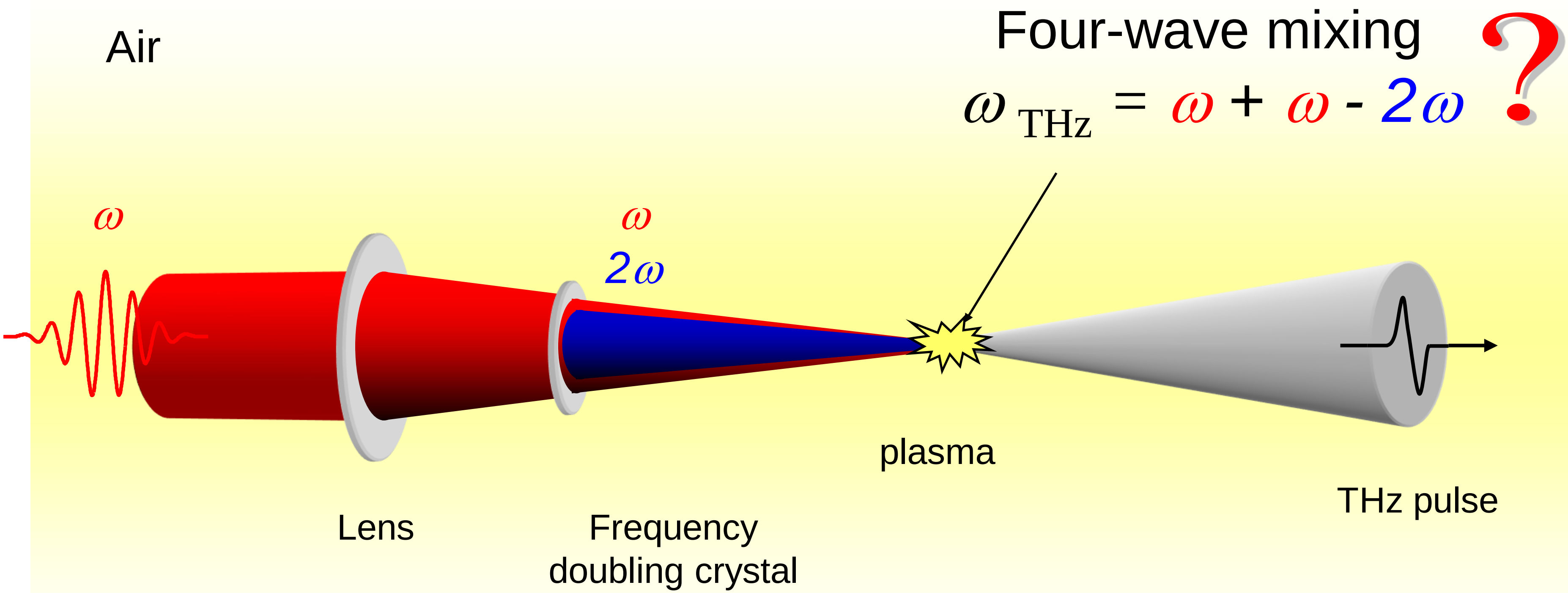
~100 ps time window, 30 fs time resolution

(10 GHz – 10 THz spectral measurement)

THz/Microwave generation:

Two-color filamentation

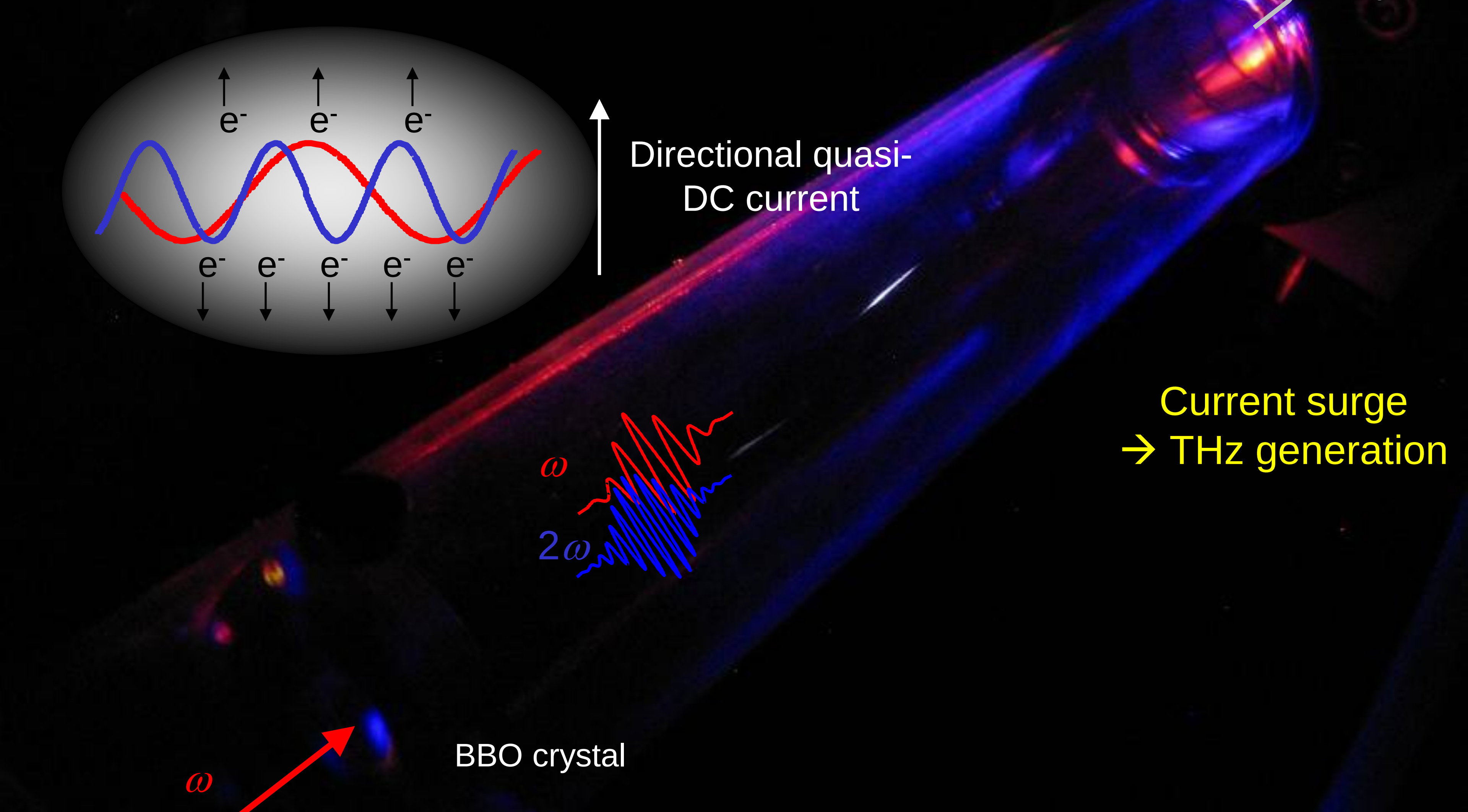
THz generation via two-color filamentation:



$$\mathbf{P}(t) = \varepsilon_0 \left(\chi^{(1)} \mathbf{E}(t) + \chi^{(2)} \mathbf{E}^2(t) + \chi^{(3)} \mathbf{E}^3(t) + \ldots \right)$$

D. J. Cook and R. M. Hochstrasser, Opt. Lett. **25**, 1210 (2000).

THz generation mechanism:
*Plasma current model**



*K. Y. Kim *et al*., Nature Photonics **2**, 605 (2008).
K. Y. Kim *et al*., Optics and Photonics News **19**, 49 (2008).

Plasma current model (semiclassical model):

Laser field

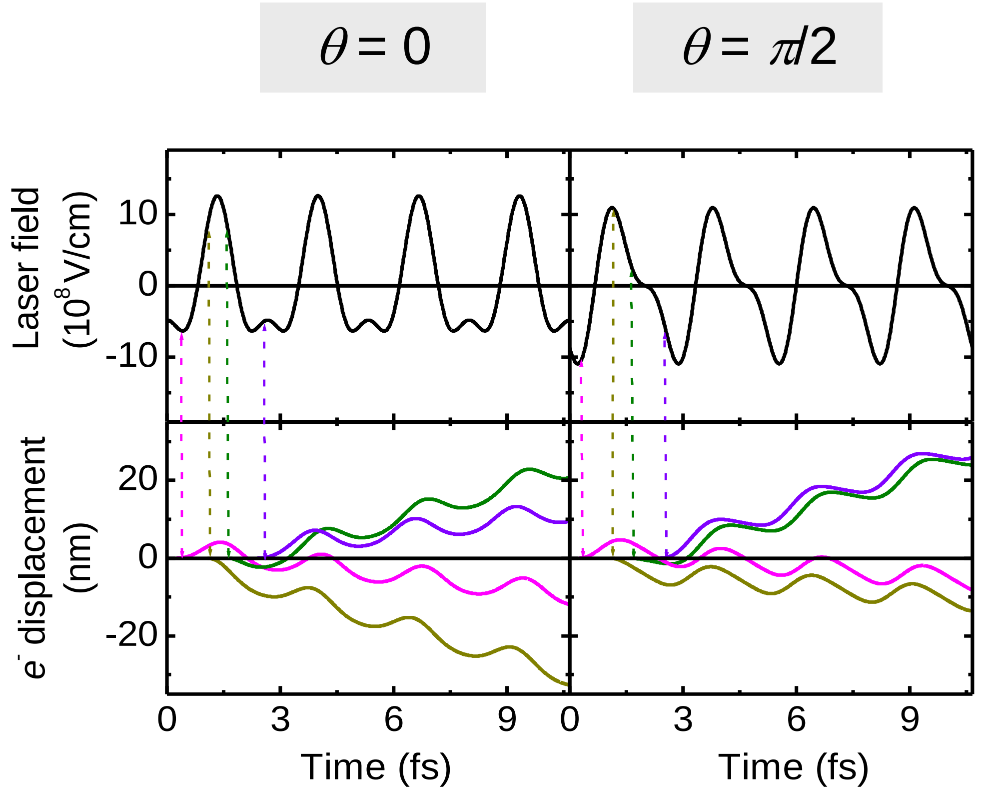
$$E_L(t) = \underbrace{E_1 \cos(\omega t)}_{\omega \text{ field}} + \underbrace{E_2 \cos[2\omega t + \theta]}_{2\omega \text{ field}}$$

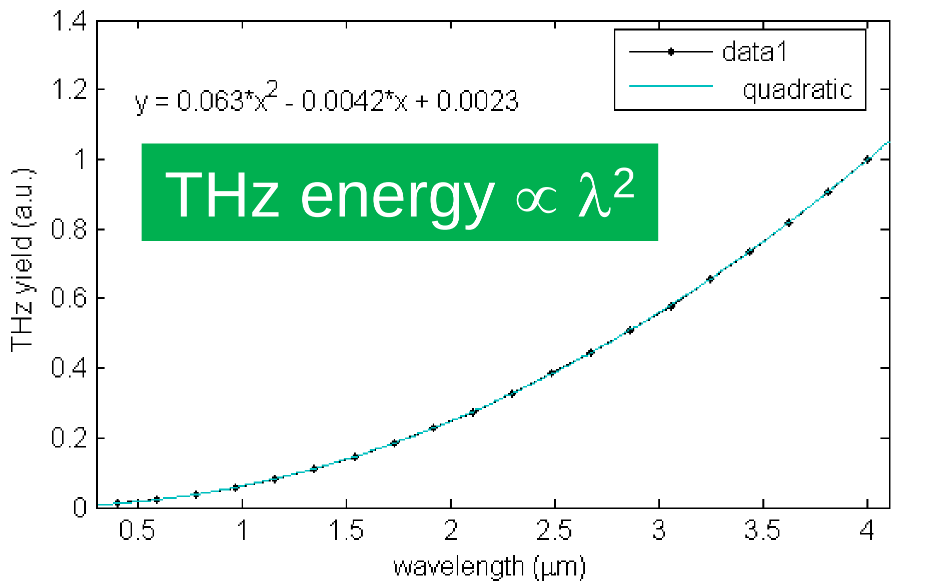
θ : relative phase

Electron drift velocity

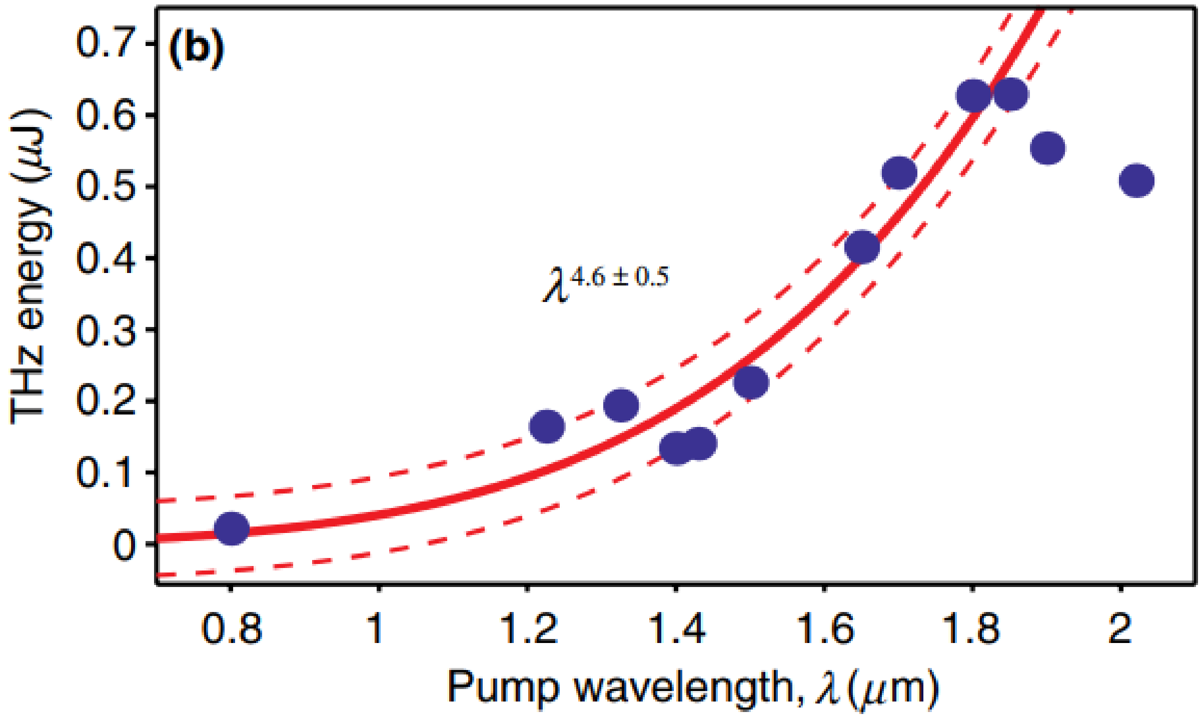
$$\upsilon_d = \frac{eE_1}{m_e\omega}\sin\phi + \frac{eE_2}{2m_e\omega}\sin(2\phi+\theta)$$

electron freed at ϕ





Wavelength scaling with two-color mixing



M. Clerici *et al*., Phys. Rev. Lett. **110**, 253901 (2013).

THz energy scaling:

Plasma current (~λ^2)

Plasma length & radius (~λ)

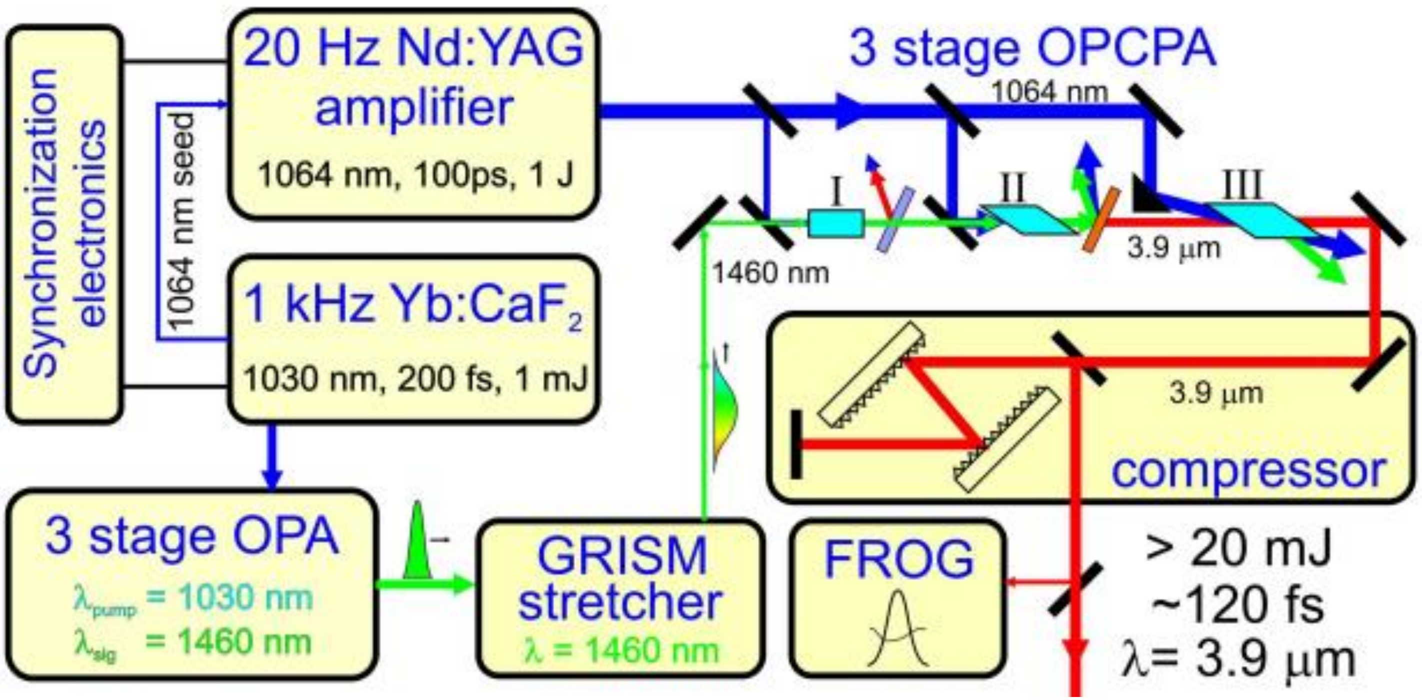
Peak intensity (~λ^{-2})

Longitudinal current $J_z^{(2)}$ (~λ^4)

Transverse current $J_x^{(3)}$ (~λ^6)

Need more studies!

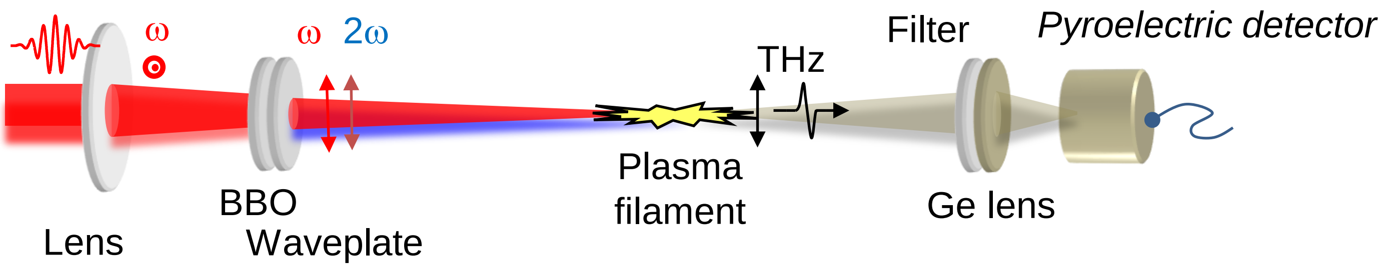
Preliminary experiment at UMD (λ = 3.9 μm)

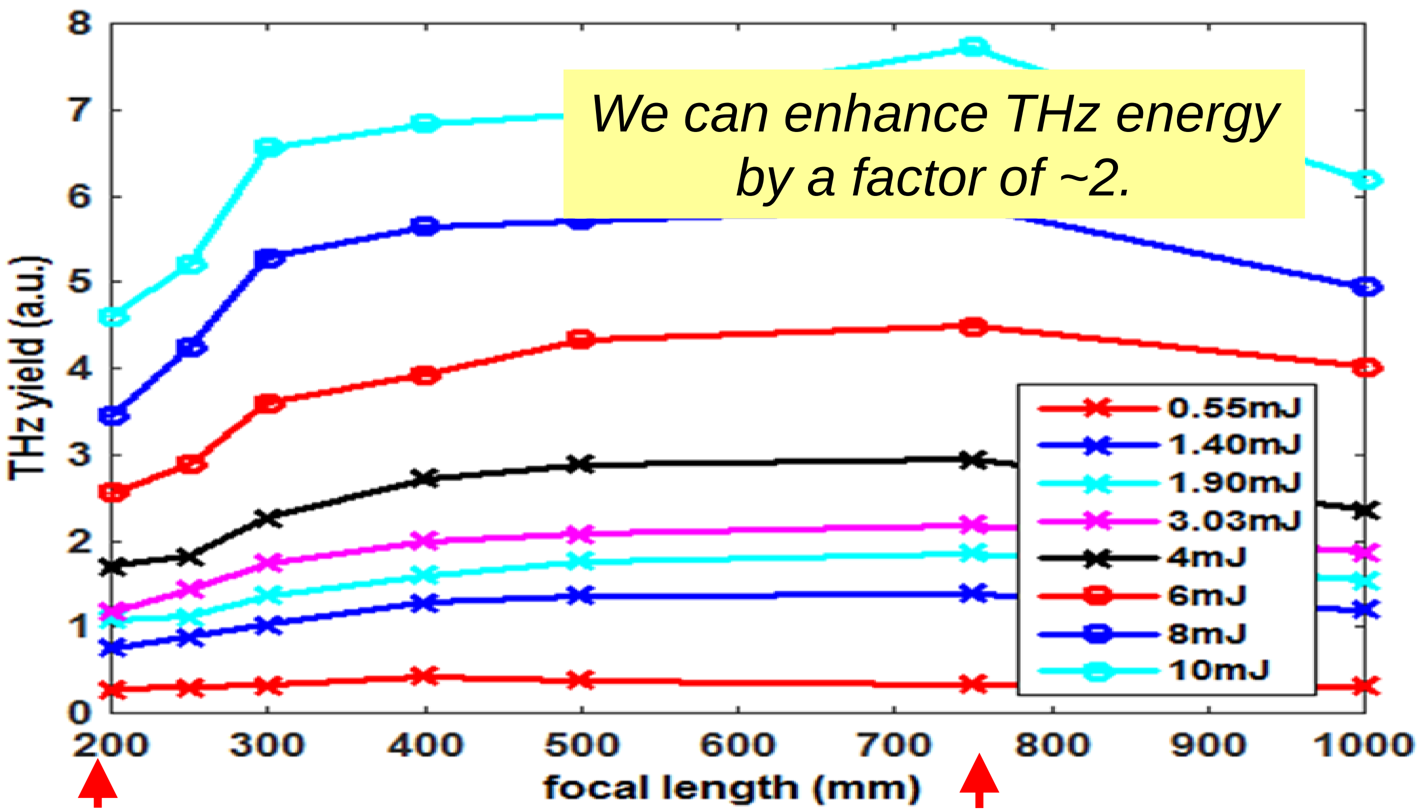


A. V. Mitrofanov *et al.*, Sci. Rep. **5**, 8368 (2015).

- THz/microwave generation with single- & two-color pulses
- THz/microwave detection with various schemes

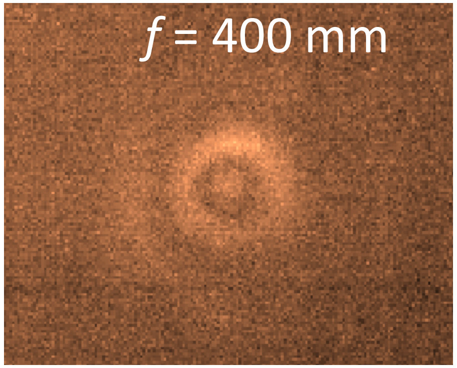
THz generation via long focusing in air

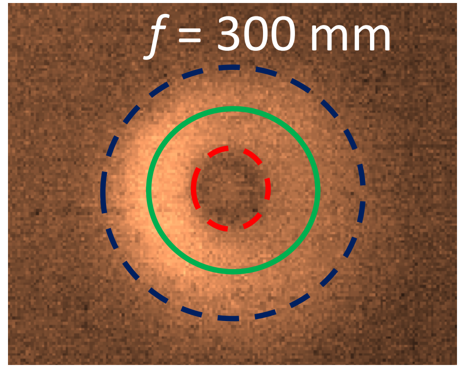


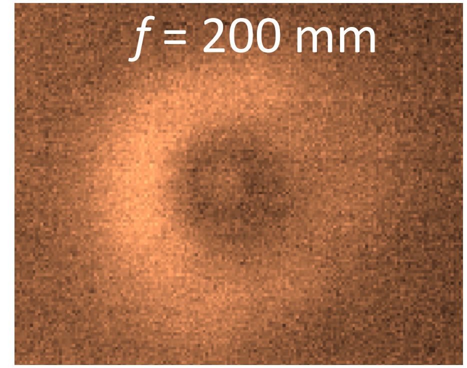


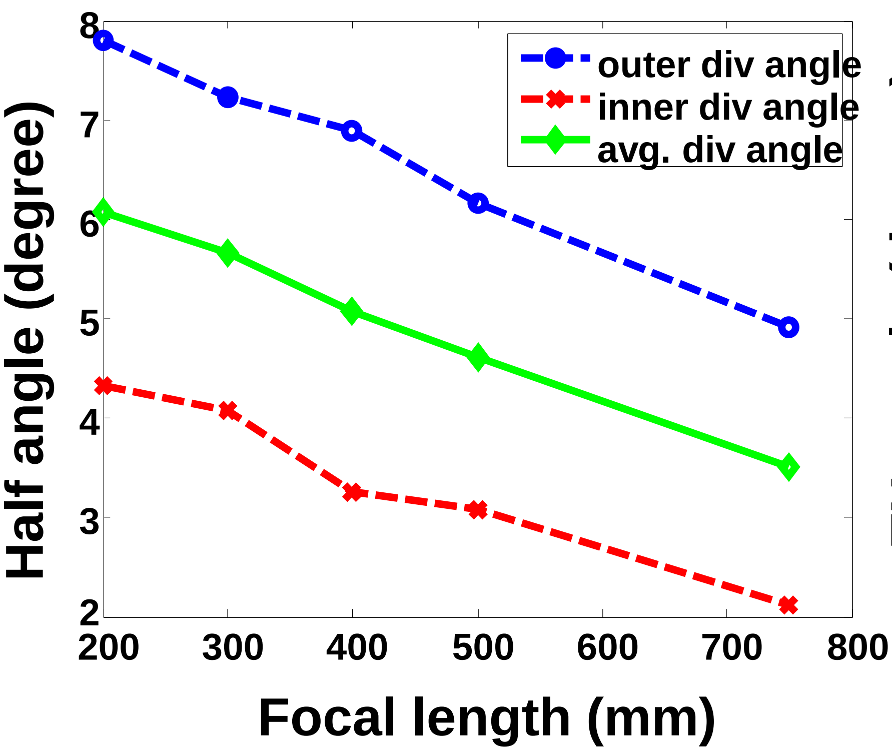
Y. J. Yoo *et al.*, IEEE JSTQE **4**, 8501007 (2017).

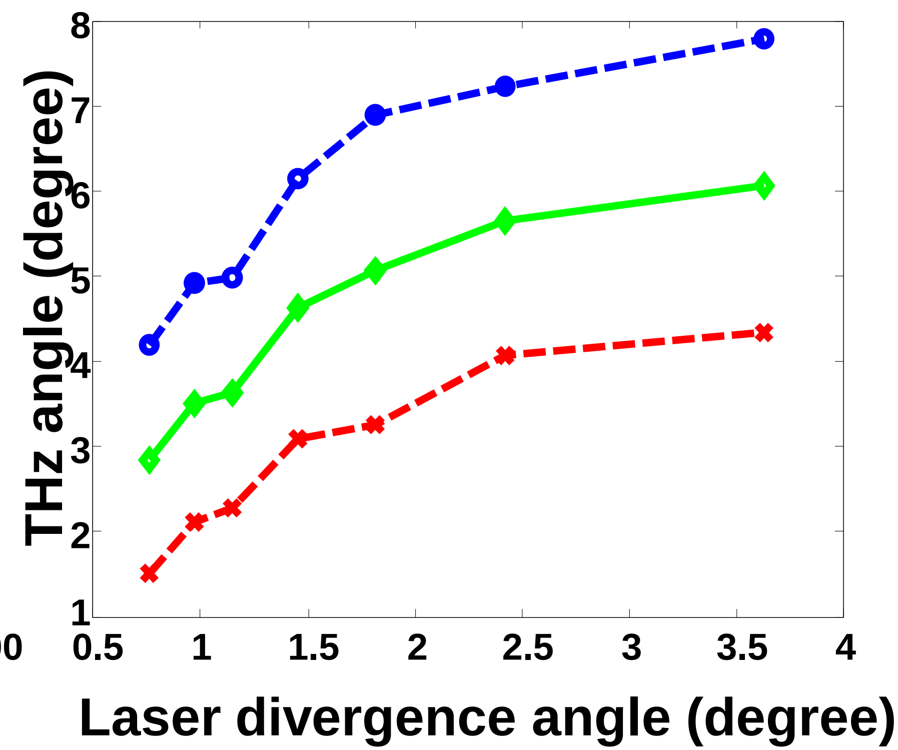
THz divergence angle





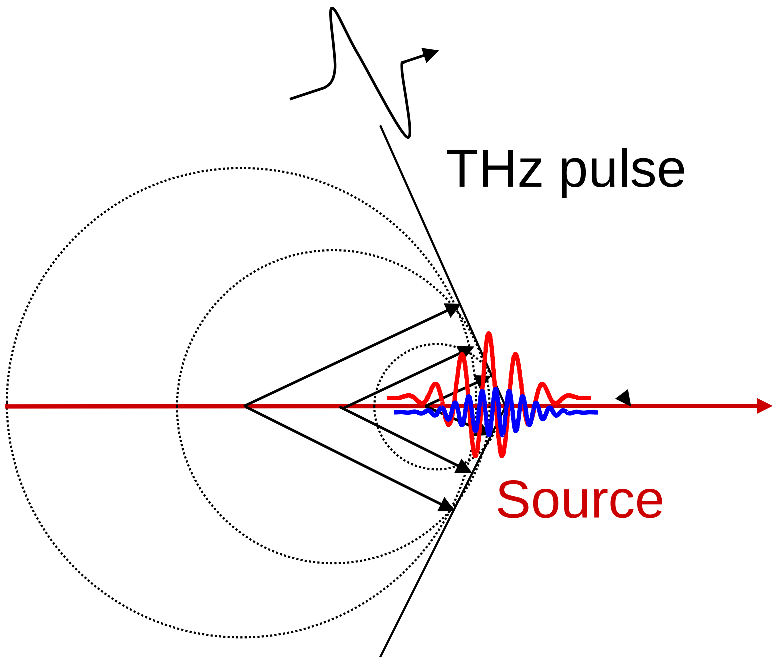




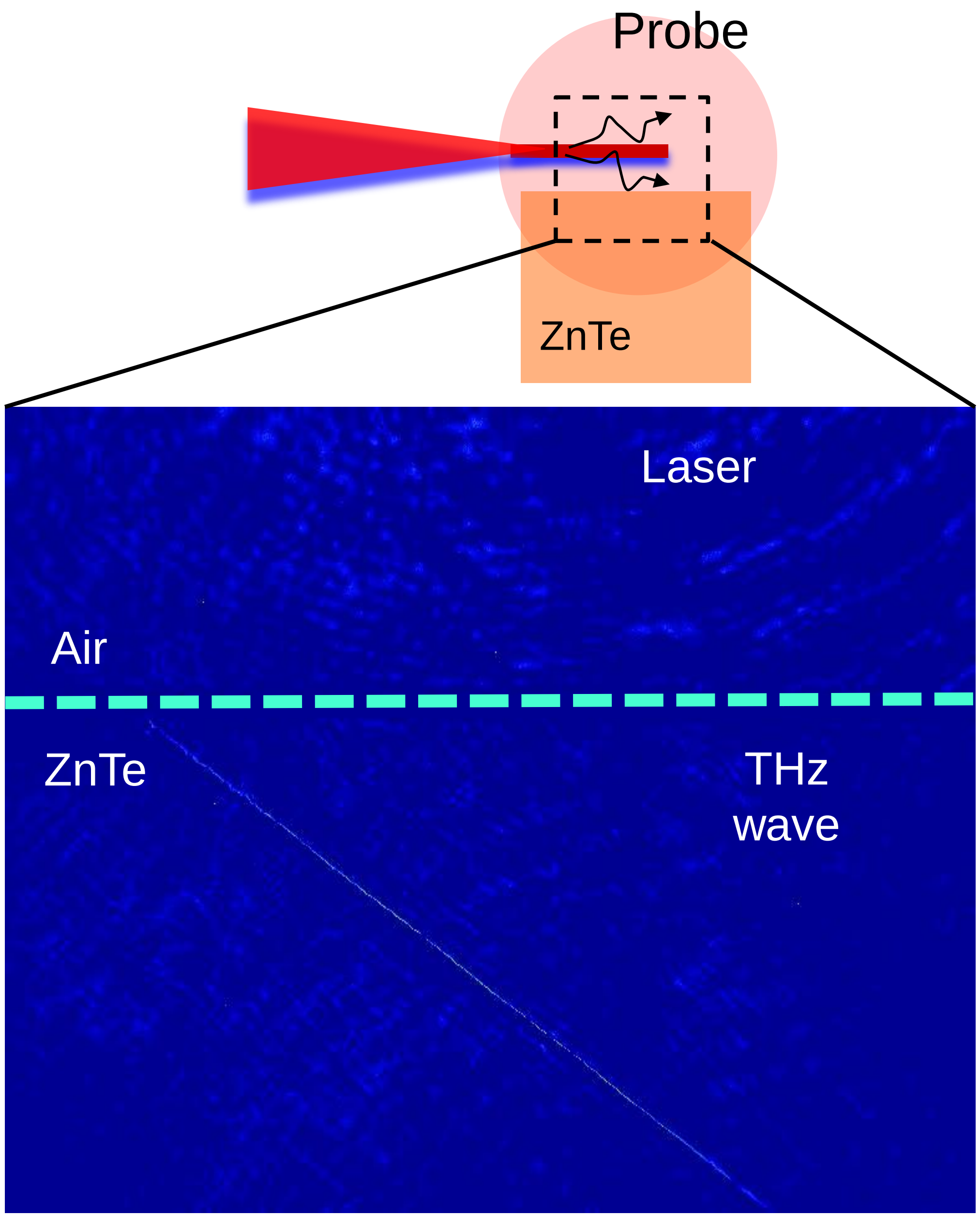


Y. J. Yoo *et al.*, IEEE JSTQE **4**, 8501007 (2017).

Conical emission: side imaging



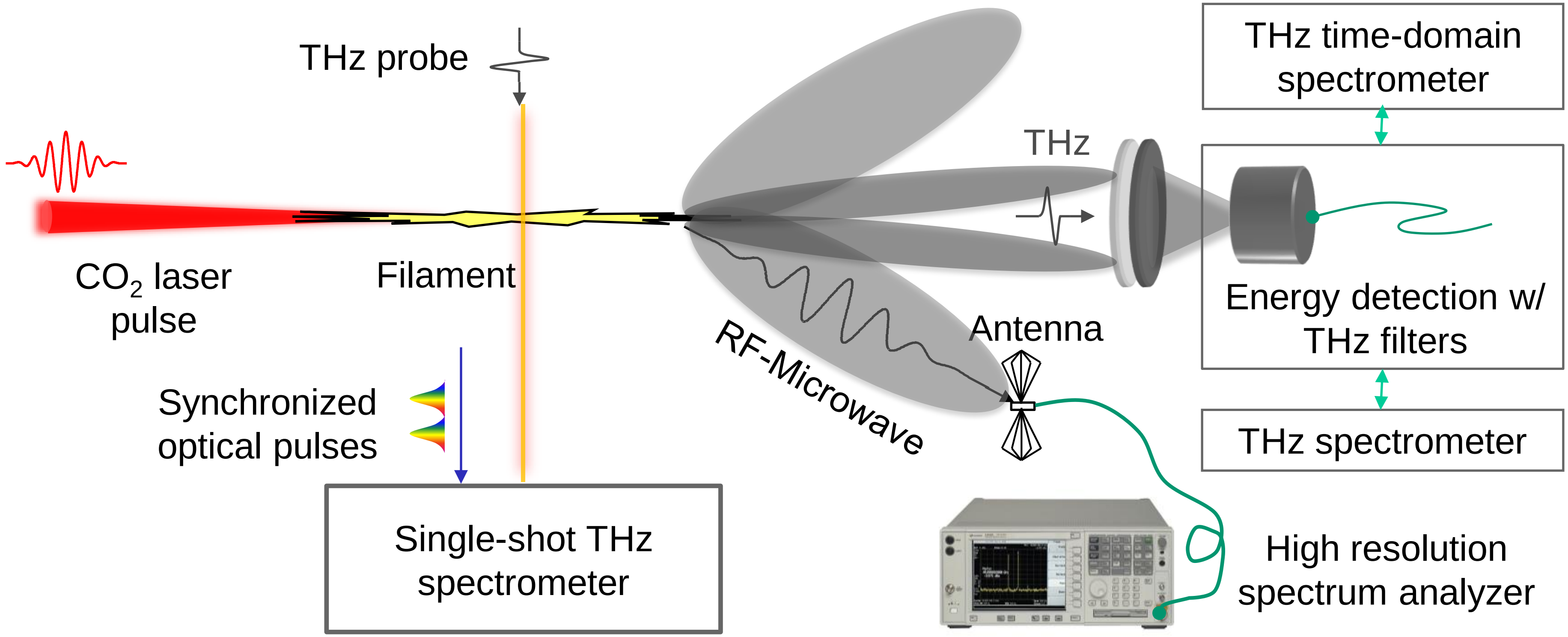
$$\mathbf{v}_{source} > \mathbf{v}_{THz}$$



Characterization of CO_2 laser produced plasmas

Plasma characterization

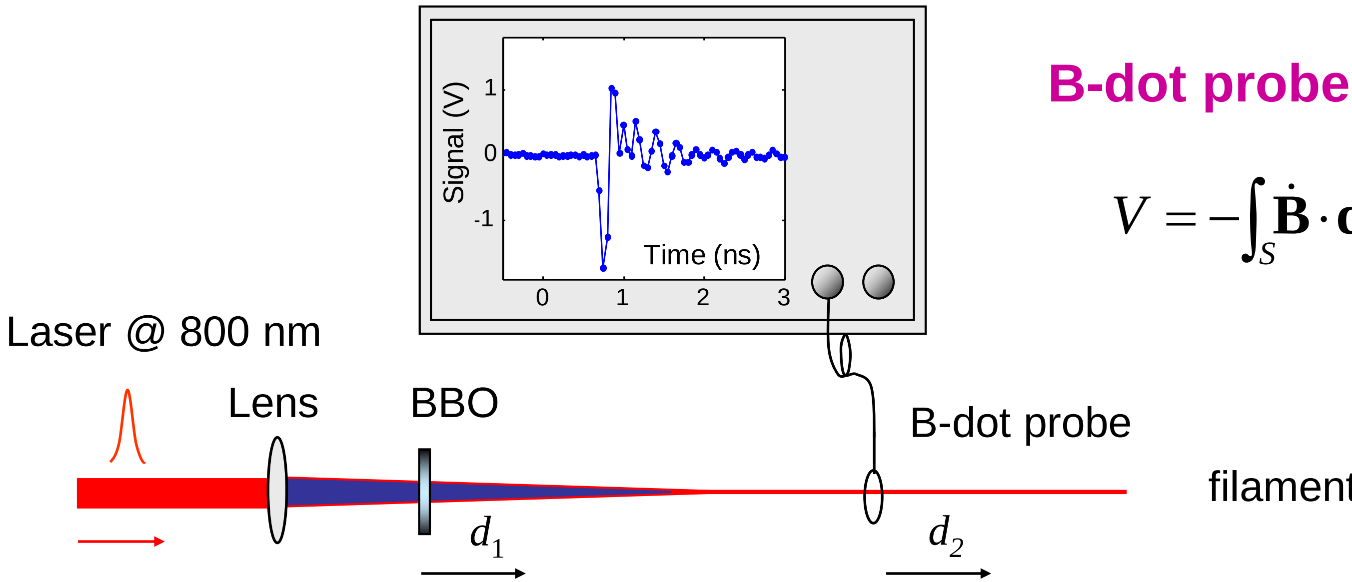
Plasma characterization by (a) active THz spectroscopy and/or (b) passive THz/microwave spectral analysis



Active THz spectroscopy

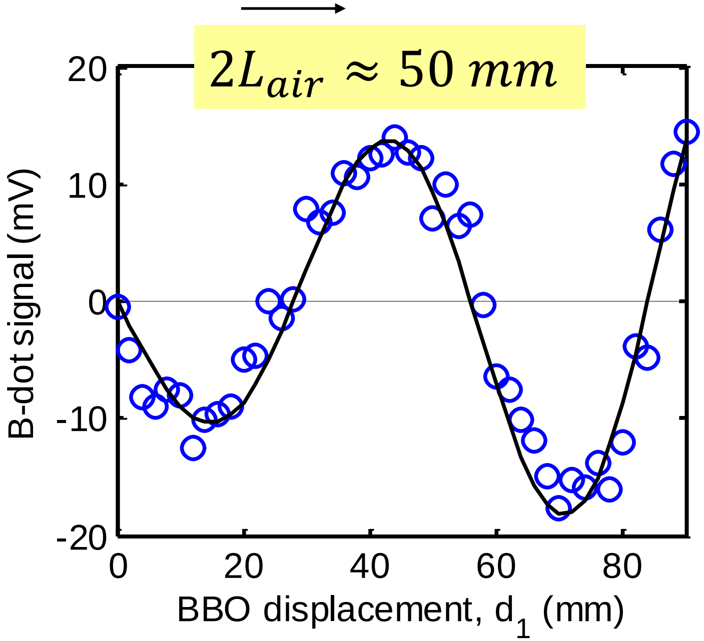
Passive THz/microwave spectrum analysis

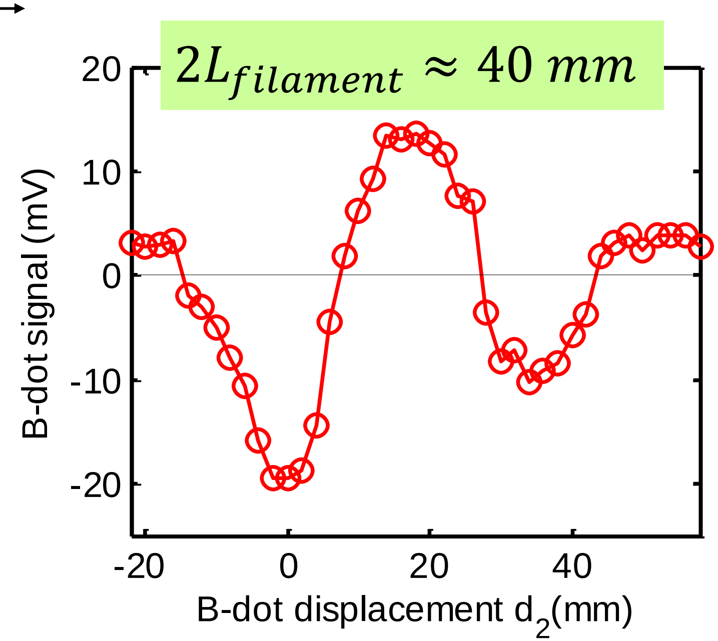
B-dot probe experiment (800 nm + 400 nm)



B-dot probe:

$$V = -\int_S \dot{\mathbf{B}} \cdot \mathbf{ds} \quad \text{(Faraday's Law)}$$





Analysis of 800 nm + 400 nm:

Dephasing length

$$L_{filament} = \frac{\lambda_\omega}{2(n_{2\omega} - n_\omega)} = \frac{\lambda_\omega}{2\left(\Delta n_{\mathrm{air}} + \Delta n_{\mathrm{plasma}}\right)}$$

$$\frac{1}{L_{filament}} = \frac{2\Delta n_{\mathrm{air}}}{\lambda_\omega} + \frac{2\Delta n_{\mathrm{plasma}}}{\lambda_\omega} = \frac{1}{L_{air}} + \frac{1}{L_{plasma}}$$

Dephasing length in air

$$L_{air} = \frac{\lambda_\omega}{2\Delta n_{\mathrm{air}}} \approx 25\ \mathrm{mm}$$

Dephasing length in pure plasma

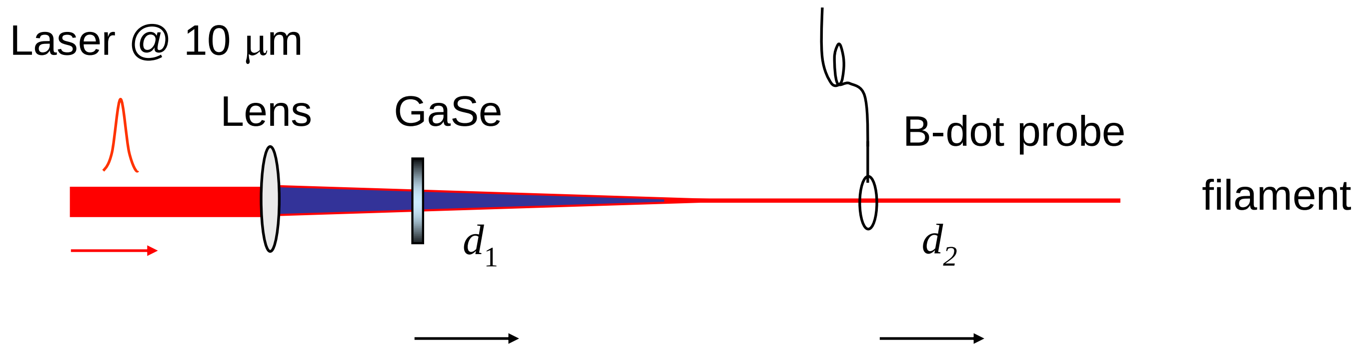
$$L_{plasma} = \frac{4}{3}\lambda_\omega (N_c/N_e)$$

$$\approx 100\ \mathrm{mm}$$

With measured $L_{filament} \approx 20\ \mathrm{mm}$

→ Electron density of $N_e \sim 2 \times 10^{16}\ \mathrm{cm}^{-3}$

B-dot probe experiment with CO_2 laser:



Refractive index of dry air at 1 atm and 288 K

$$n_{air,10\mu m} \approx 1 + 272.6 \times 10^{-6}$$

$$n_{air,5\mu m} \approx 1 + 272.7 \times 10^{-6}$$

Dephasing length in air

$$L_{air} = \frac{\lambda_\omega}{2\Delta n_{\mathrm{air}}} \approx 50\ \mathrm{m}$$

Dephasing length in pure plasma

$$L_{plasma} = \frac{4}{3}\lambda_\omega (N_c/N_e)$$

$$\approx 10\ \mathrm{m} \ \text{ with } N_e \approx 10^{13}\ \mathrm{cm}^{-3}$$

We can measure the electron density down to $N_e \sim 10^{13}$ cm^{-3}

Summary:

- **THz/microwave emission from 10 μm filamentation:**
  - THz/microwave generation mechanisms (microscopic and macroscopic) in single-color and two-color filamentation in air
  - Favorable wavelength scaling for THz/microwave generation

- **THz/microwave detection:**
  - Characterization of THz/microwave radiation
  - Development of high-resolution THz spectroscopy with a fs laser

- **Characterization of CO2 laser produced filaments:**
  - Plasma characterization with THz/microwave spectral analysis
  - Plasma density measurement with a B-dot probe
  - Active THz spectroscopy with a femtosecond laser

- **Anticipate exciting results over the next 5 years!**