Intense THz Pulse Generation and Measurement

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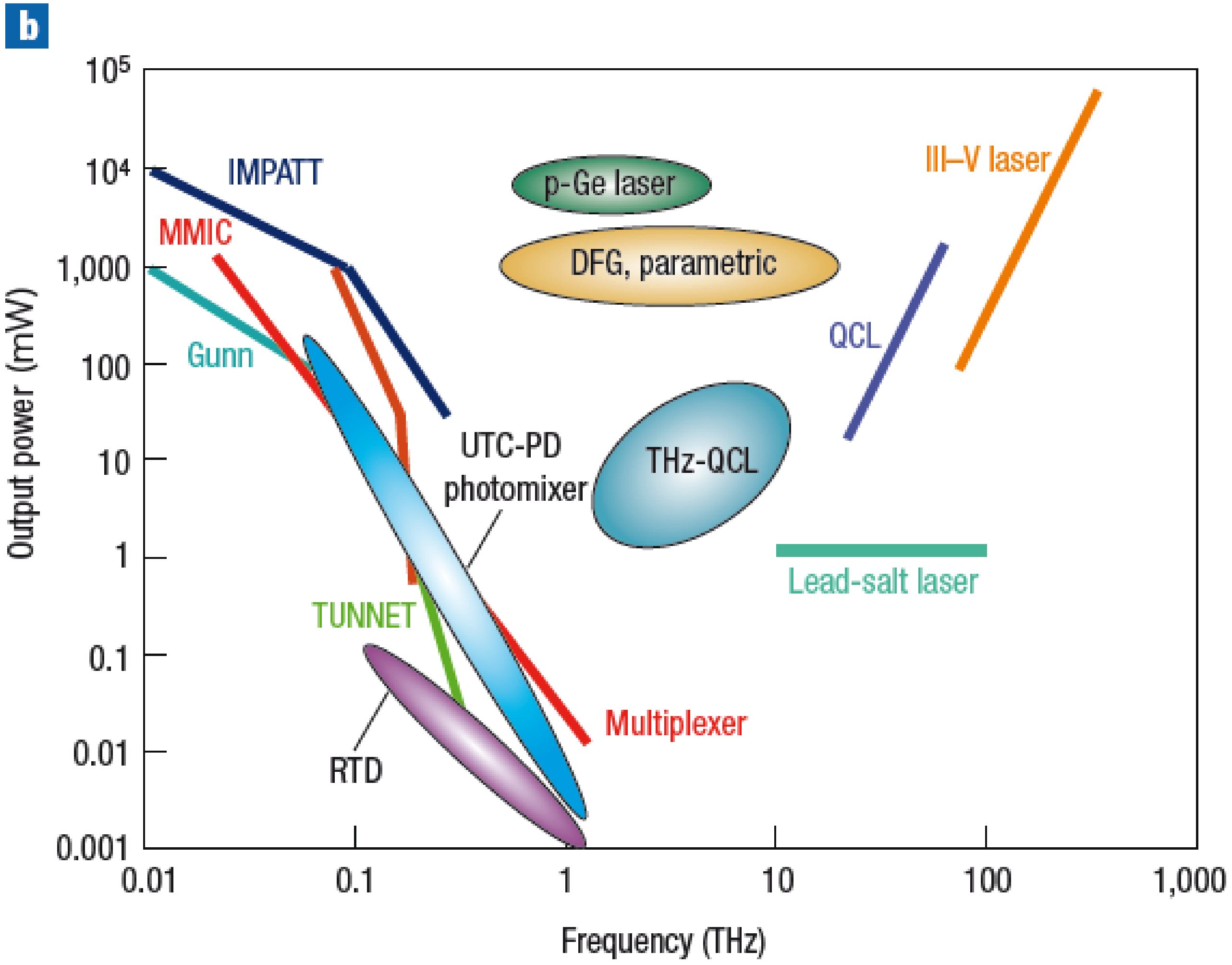
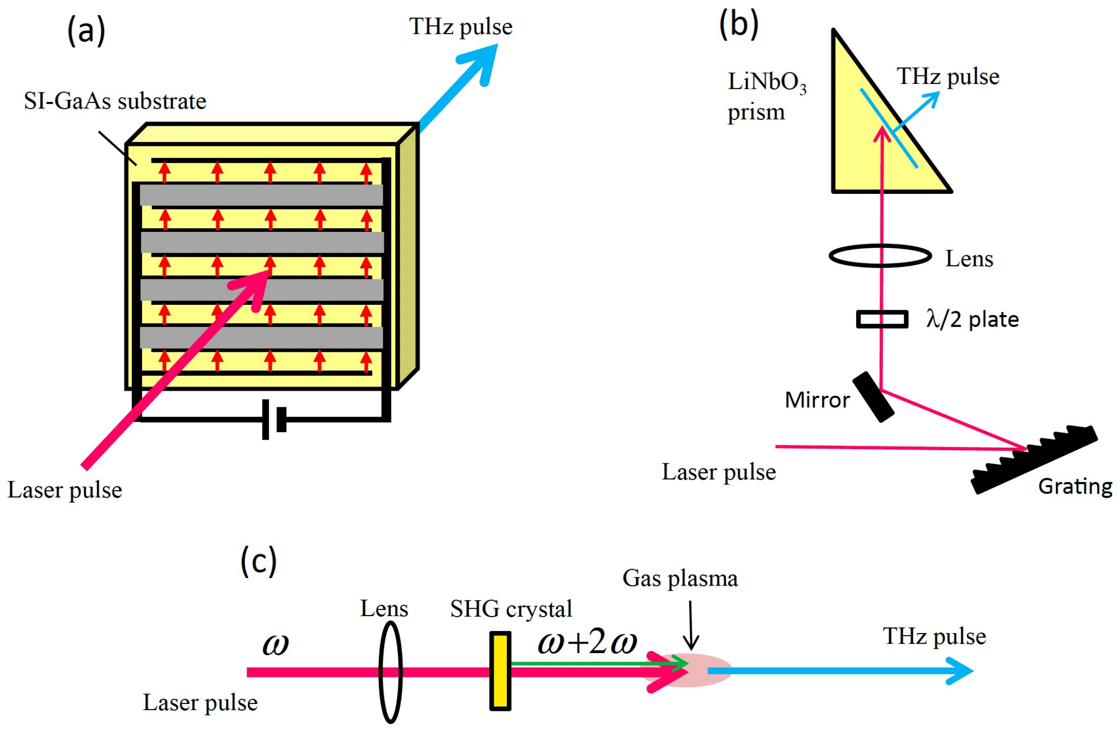
THz pulse generation

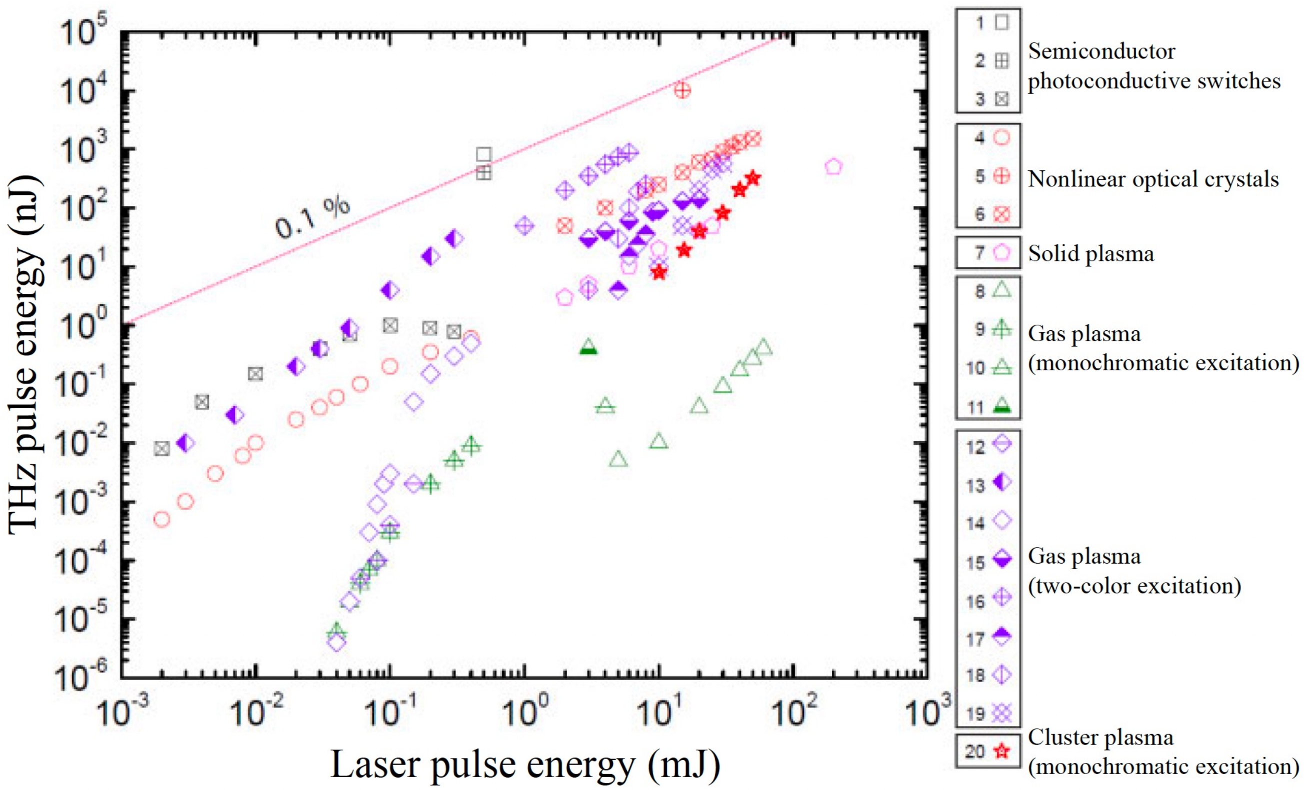
THz sources



Tonouchi, M. Cutting-edge terahertz technology. *Nature Photon* **1**, 97–105 (2007).

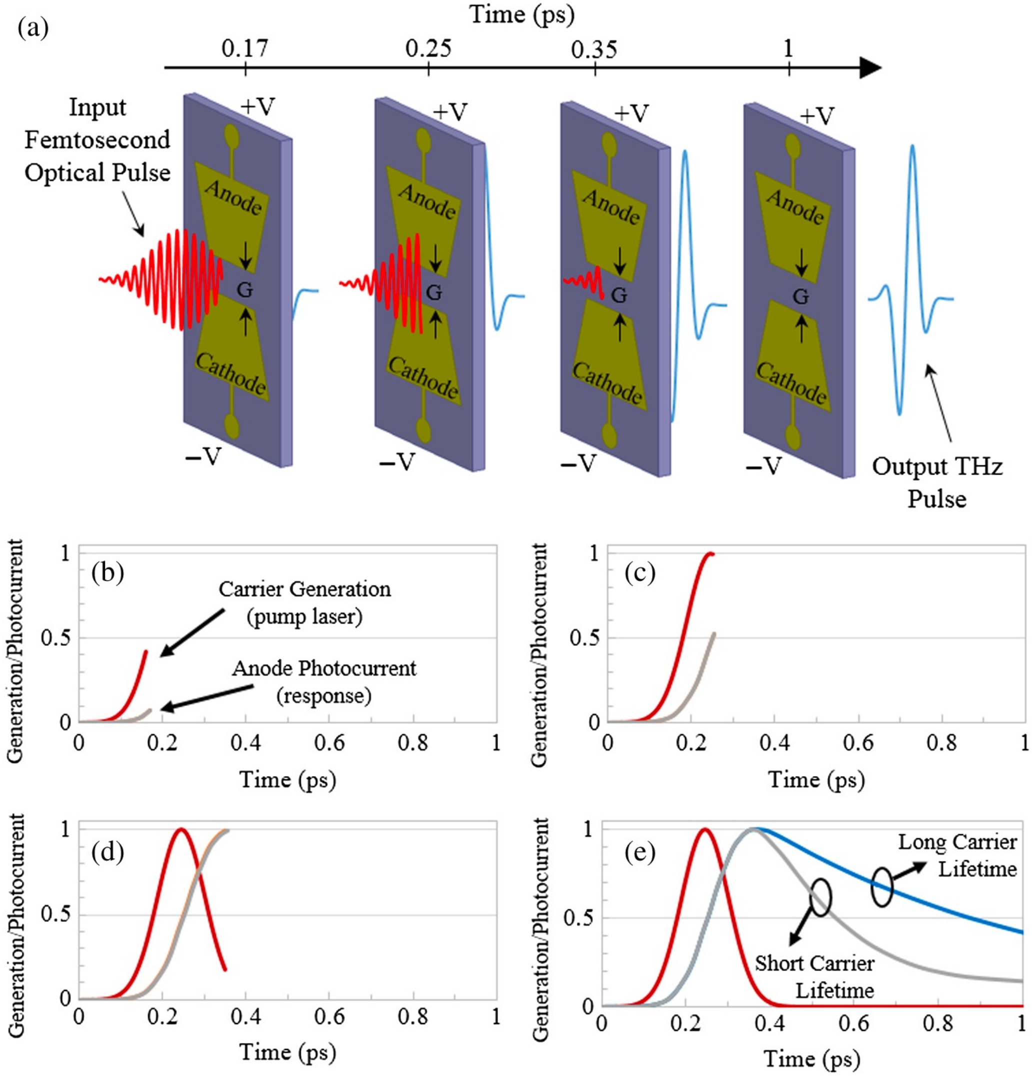
Overview of laser-based THz generation

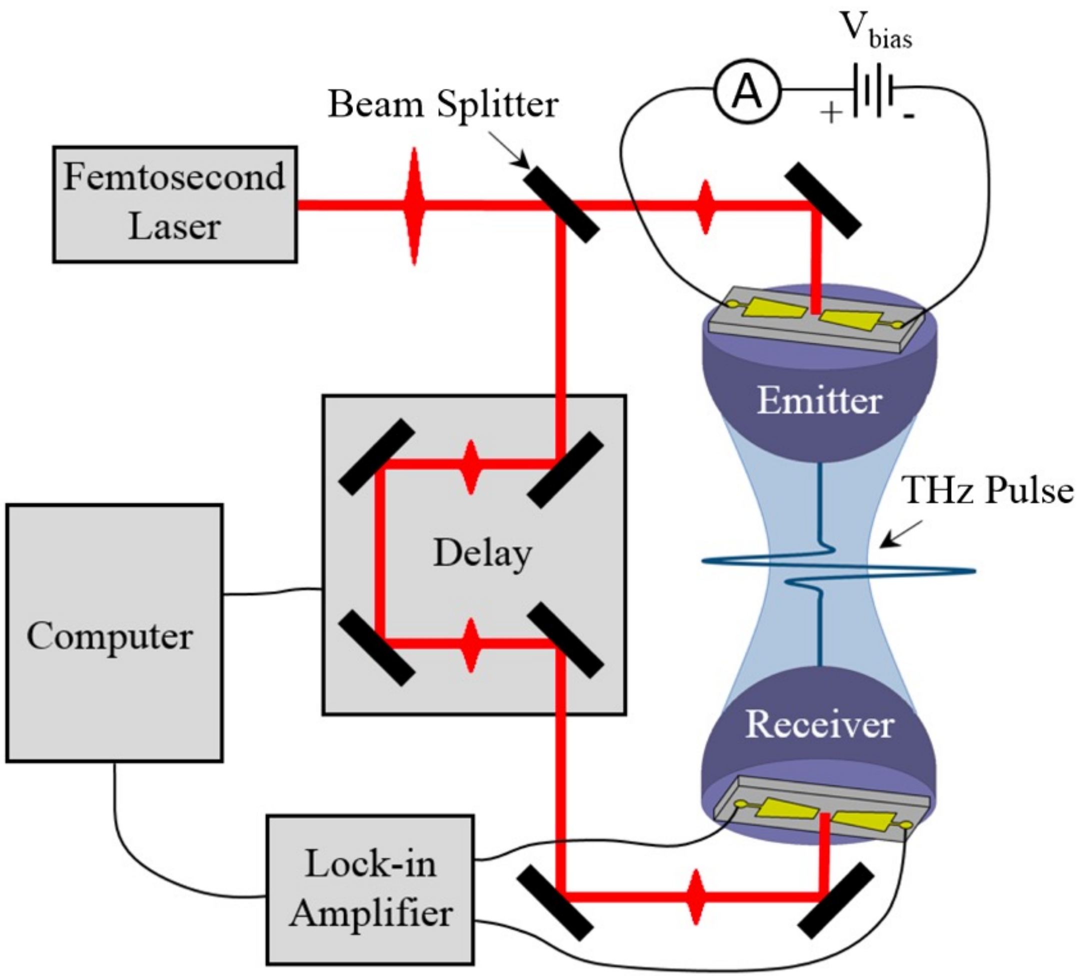




Masanori Hangyo 2015 Jpn. J. Appl. Phys. 54 120101

Photoconductive antenna

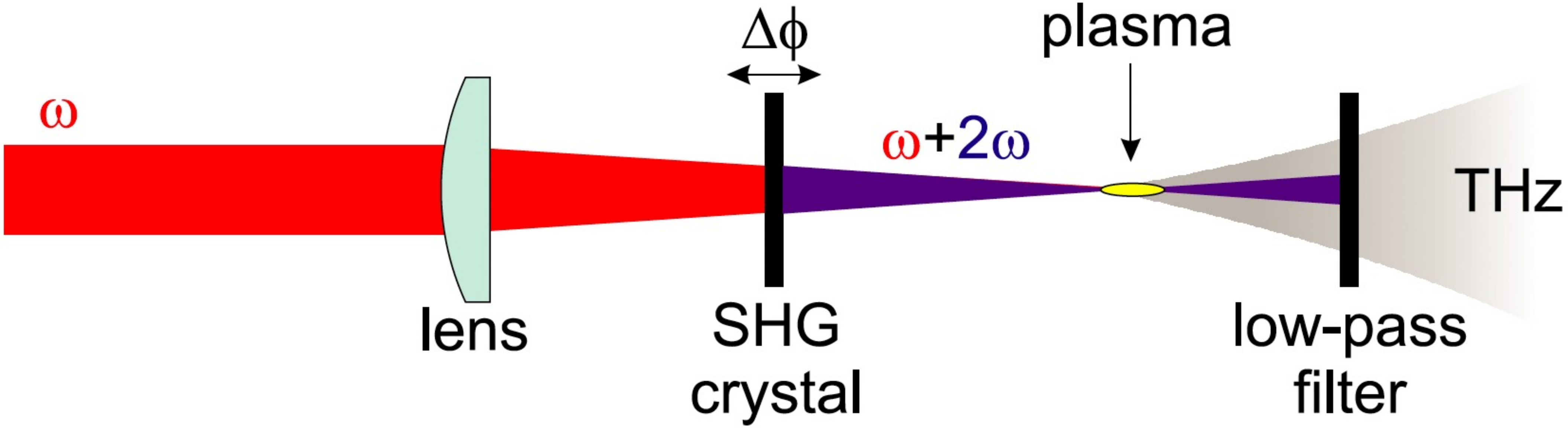




Optical Engineering, Vol. 56, Issue 1, 010901 (January 2017)

Air plasma

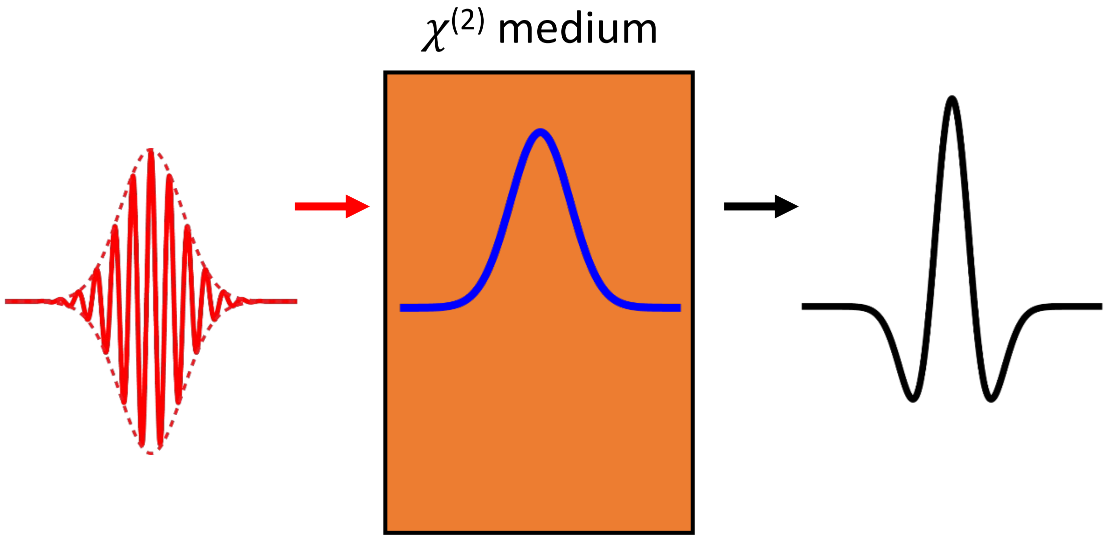
$2\omega - \omega - \omega = 0$



Matthias C Hoffmann and József András Fülöp 2011 *J. Phys. D: Appl. Phys.* **44** 083001

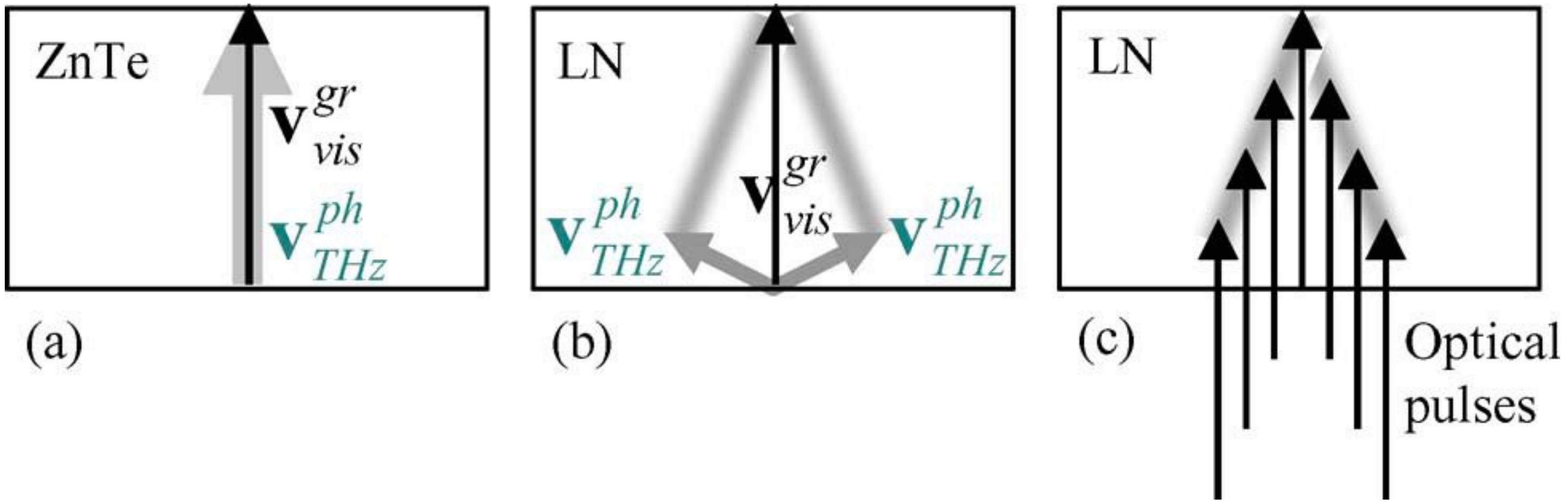
Optical rectification $\omega - \omega = 0$

$$\nabla^2 \overline{E}_{THz} - \frac{\varepsilon_r(\omega)}{c^2}\frac{\partial^2}{\partial t^2}\overline{E}_{THz} = \frac{1}{\varepsilon_0 c^2}\frac{\partial^2}{\partial t^2}\overline{P}^{NL}$$



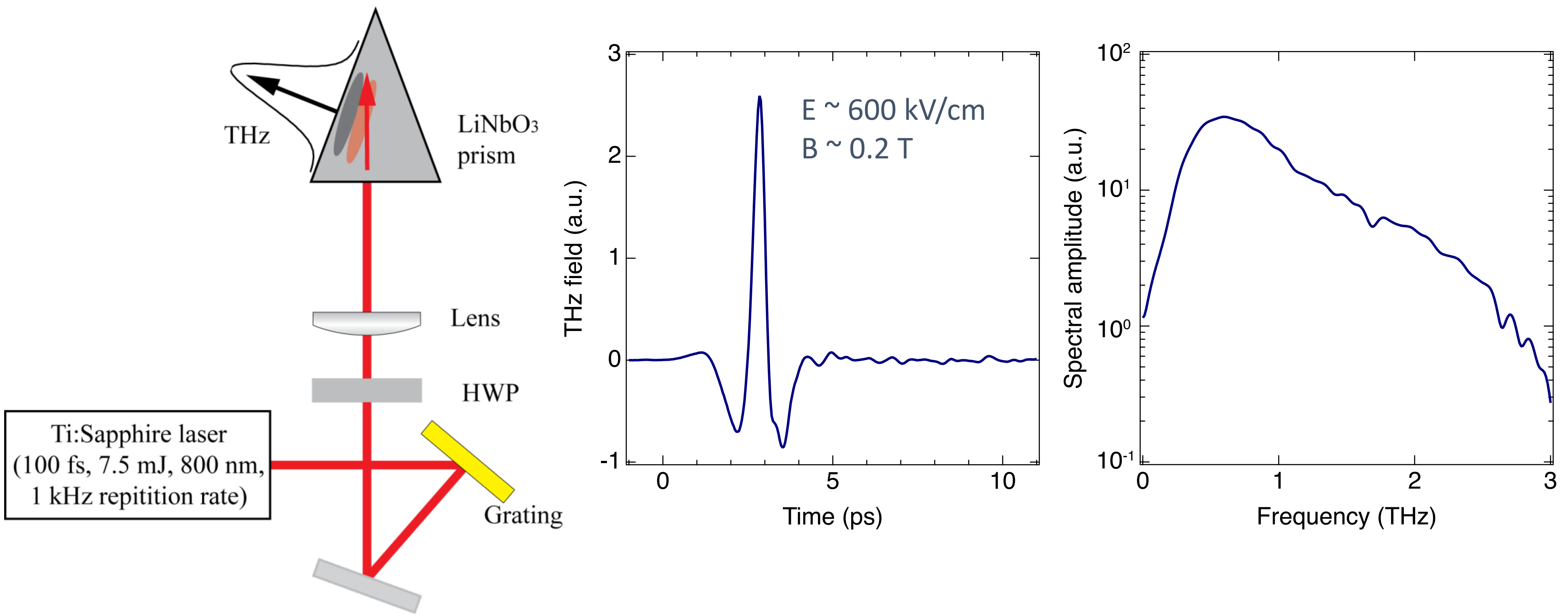
fs laser pulse E $P^{\mathrm{NL}} \propto EE^*$ $E_{\mathrm{THz}} \propto \frac{\partial^2 P^{\mathrm{NL}}}{\partial t^2}$

Phase matching condition for OR



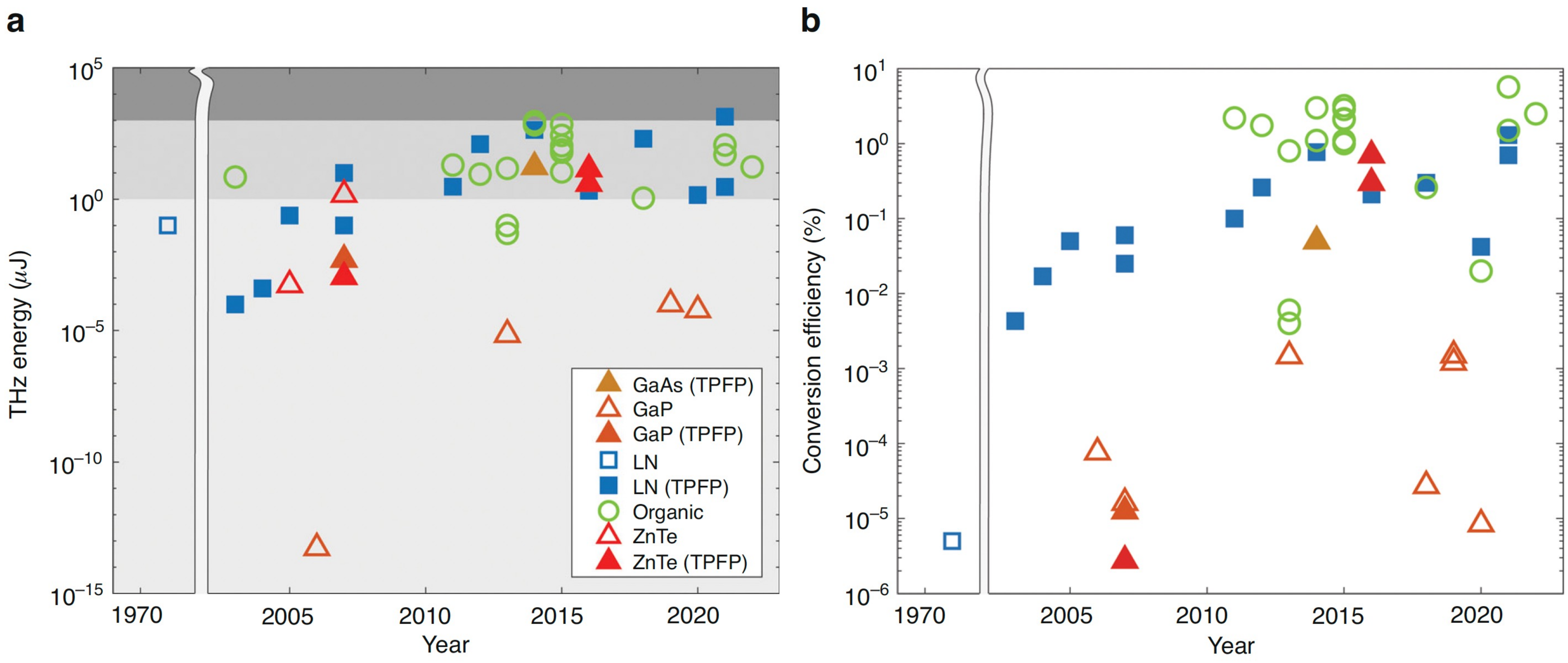
J. Hebling, K. -L. Yeh, M. C. Hoffmann and K. A. Nelson, "High-Power THz Generation, THz Nonlinear Optics, and THz Nonlinear Spectroscopy," in *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 14, no. 2, pp. 345-353, March-april 2008

Tilted pulse front in $LiNbO_3$



J. Hebling et al, Opt. Express **10**, 1161(2002)
K.-L. Yeh et al, *Appl. Phys. Lett*. **90**, 171121(2007)

Intense THz pulses



Tóth, G., Polónyi, G. & Hebling, J. Tilted pulse front pumping techniques for efficient terahertz pulse generation. *Light Sci Appl* **12**, 256 (2023).

THz pulse detection

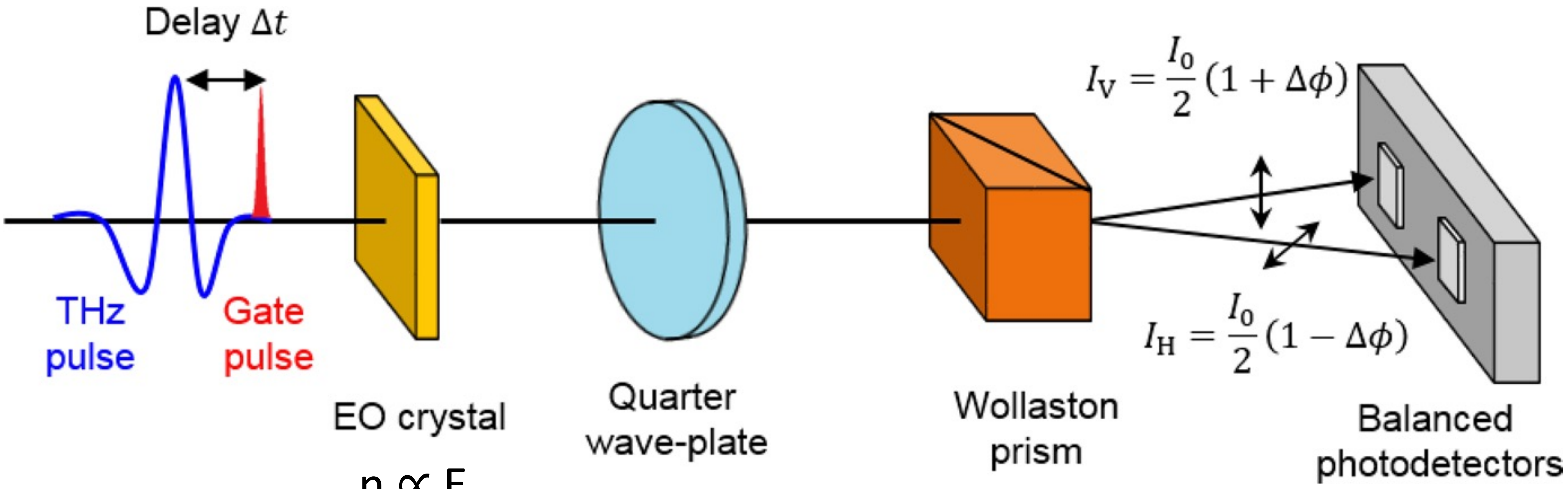
Table 2. Typical THz Detectors/Cameras Operating at Room Temperature

Detector	Detection Principle	NEP[a] ($pW/\sqrt{Hz}$)	Array	References
Thermal				
Microbolometer	Resistive change by thermal excitation	~10–100	Possible (Section 4.1)	[52–54]
Pyroelectric detector	Polarization change by thermal excitation of a pyroelectric crystal	~10–1000	Possible (Section 4.1)	[55–57]
Golay cell	Pressure change by thermal excitation of an encapsulated gas	~100–1000	Single-pixel	[58]
Mixer				
Schottky-barrier diode	High-frequency detection enabled by fast switching speeds in metal/semiconductor junction	~10–100	Possible	[59,60]
Plasmonic detector				
Field-effect transistor	Plasmonic excitation of electronic charge densities in transistor channels	~10–100	Possible (Section 4.2)	[61–63]
Optically triggered (THz-TDS)				
Photoconductive antenna	Ultrafast photoexcitation of charge carriers in a semiconductor gap	—	Possible (Section 3.3)	[40–46]
Electro-optic sampling	Birefringence-induced by THz pulse in nonlinear media	—	Possible (Section 3.4)	[64–68]
Air-biased-coherent-detection (ABCD)	THz field-induced second harmonic (TFISH) in plasma gas	—	Single-pixel	[69,70]

[a]The noise-equivalent power (NEP) is defined as the input power that gives a signal-to-noise ratio of 1 with a 1 Hz output bandwidth. It is a measure of the minimum detectable power, and a lower NEP indicates a more sensitive detector.

Guerboukha et al. Adv. Opt. Photonics 2018

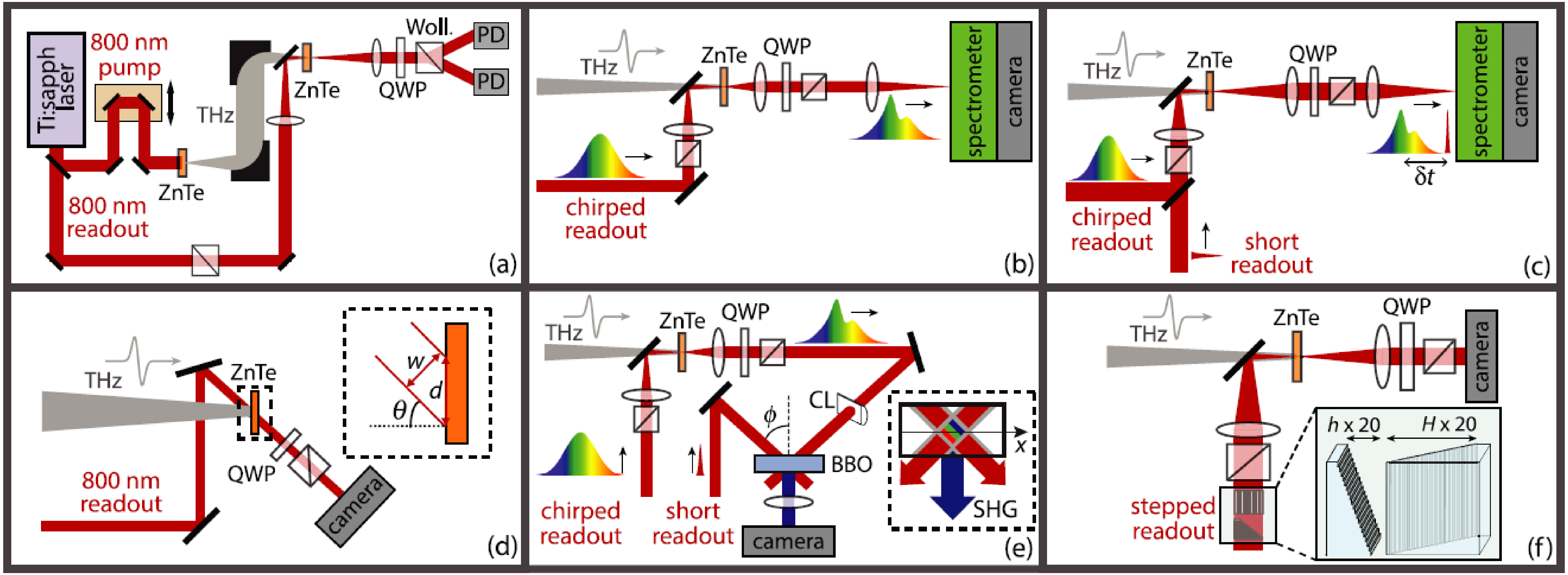
THz field detection by electro-optic sampling



$n \propto E$

Lu, J., Li, X., Zhang, Y. *et al.* Two-Dimensional Spectroscopy at Terahertz Frequencies. *Top Curr Chem (Z)* **376**, 6 (2018).

Single-shot THz detection



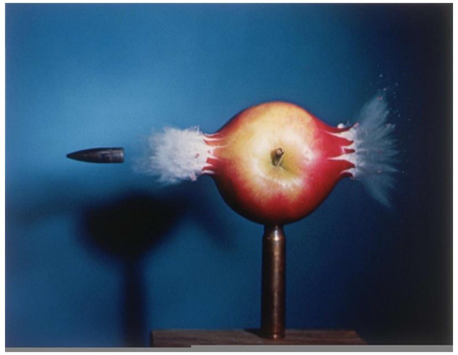
Teo et al, Rev. Sci. Instrum. (2015)

Ultrafast THz spectroscopy

Ultrafast optics

Unit	Size	Notes
attosecond	10^{-18} s	shortest time now measurable by scientists
femtosecond	10^{-15} s	pulse width on world's fastest lasers
picosecond	10^{-12} s	switching time of the world's fastest transistor
nanosecond	10^{-9} s	time for molecules to fluoresce
microsecond	10^{-6} s	length of time of a high-speed, strobe light flash
millisecond	0.001 s	time for a housefly's wing flap

Ultrafast Optics
(too fast to be monitored
with electronics)



Harold Eugene Edgerton, MIT

Ultrafast laser pulses (ps ~ as)

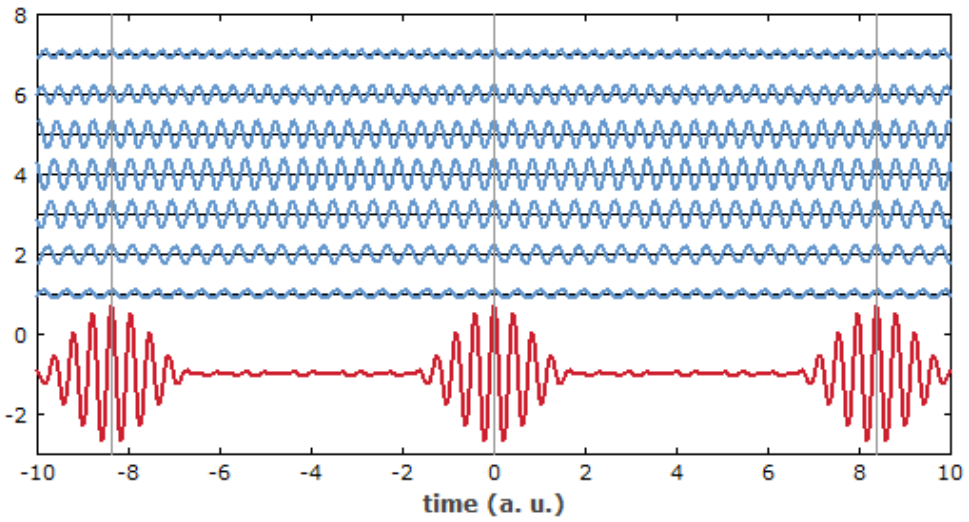
Why?

- High peak power or intensity
  - Nonlinearity
  - Laser machining
- Short duration
  - Excite materials "instantly"
  - Ultrafast snapshot
  - Monitor dynamics with high temporal resolution
- Broad bandwidth
  - Spectroscopy

How?

- Large bandwidth
- Phase correlation (Modelocking)

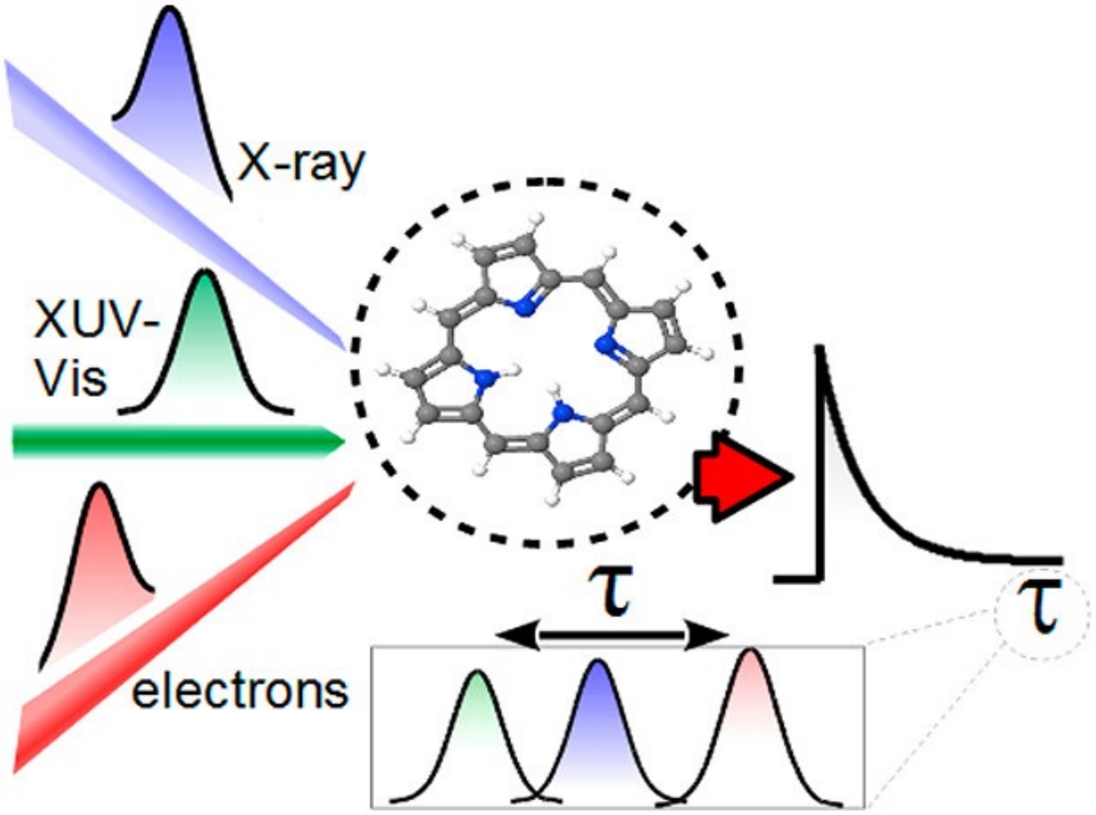
1mJ/100fs=10GW



RP Photonics Encyclopedia

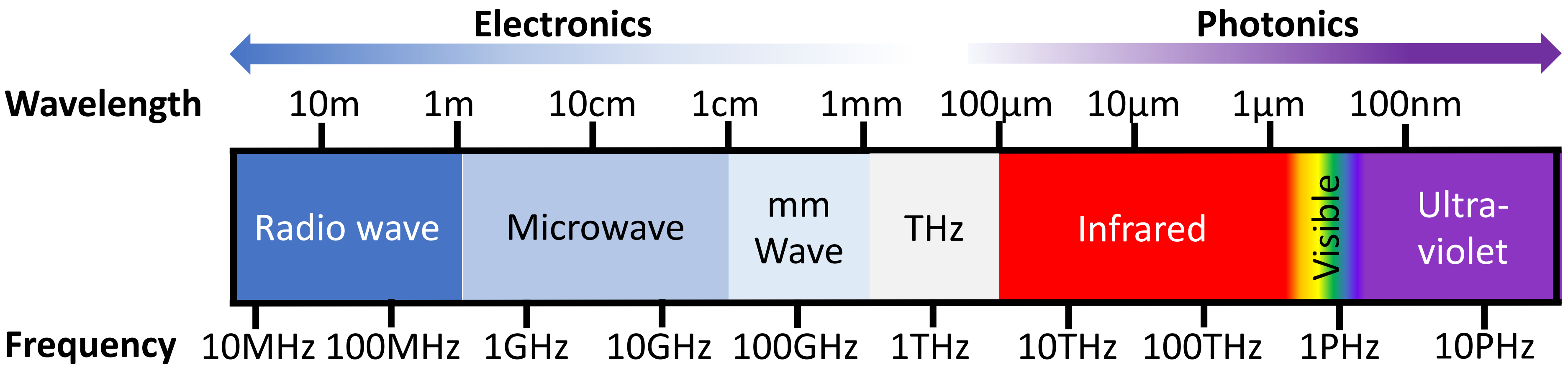
Pump-probe spectroscopy

Excite the sample and observe what happened in the femtosecond timescale



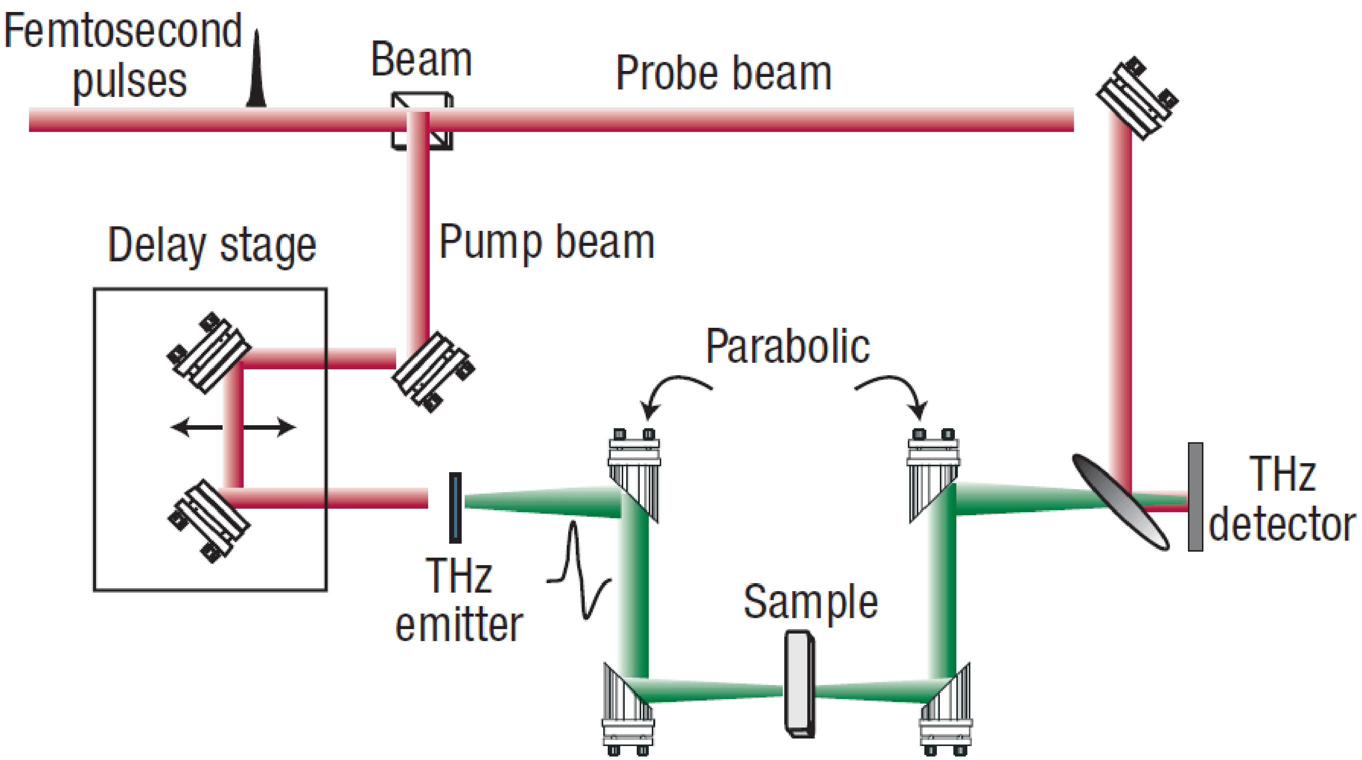
J. Am. Chem. Soc. 2020, 142, 1, 3-15

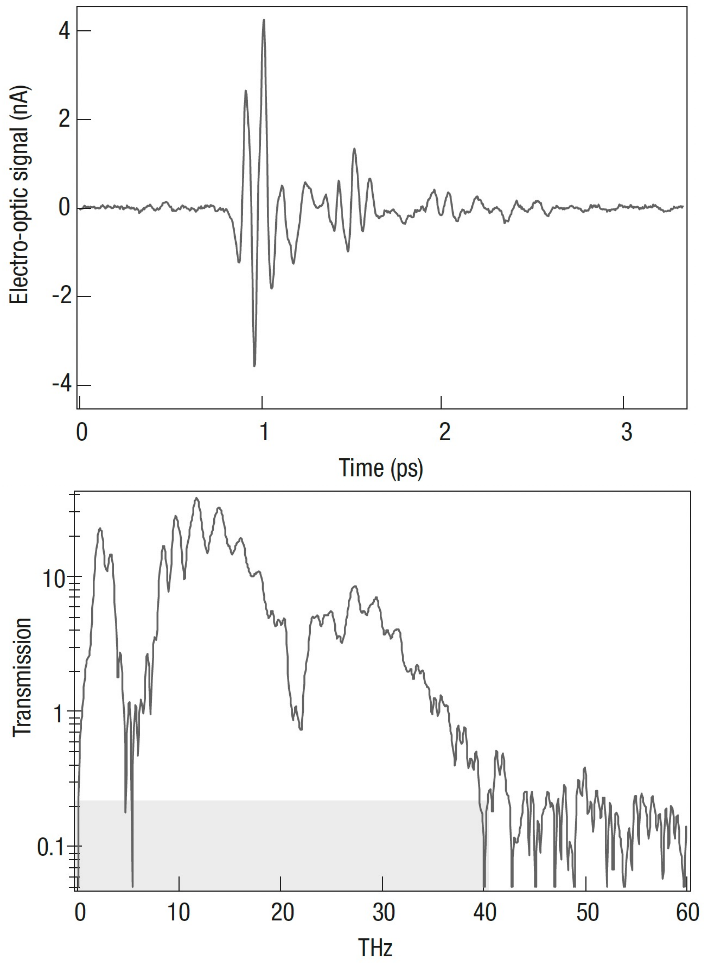
Terahertz gap



1 THz = 1 ps = 33 cm^{-1} = 0.3 mm = 4.1 meV = 48 K

THz time-domain spectroscopy



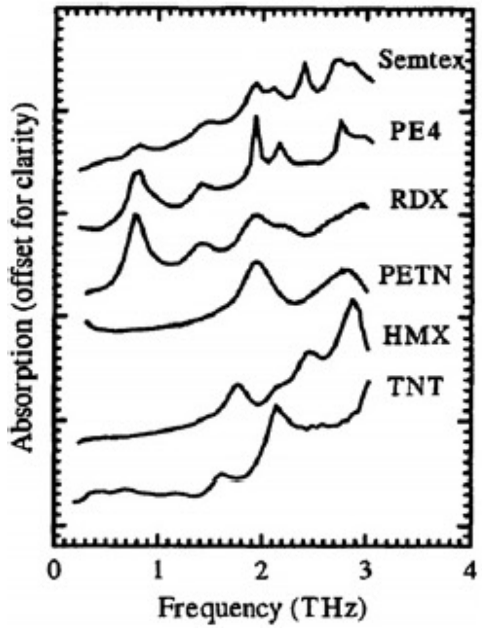


Measure THz in time domain and then Fourier transform

Ferguson, B., Zhang, XC. Materials for terahertz science and technology. *Nature Mater* **1**, 26–33 (2002).

Identify explosives and drugs

Table 1. Collection of absorbance peak positions of some explosives and drugs. Conversion to units of wavenumbers requires multiplication by 33 cm^{-1} = 1 THz.



Material	Feature band centre position frequency (THz)	Reference
Explosive		
Semtex-H	0.72, 1.29, 1.73, 1.88, 2.15, 2.45, 2.57	[12]
PE4	0.72, 1.29, 1.73, 1.94, 2.21, 2.48, 2.69	[12]
RDX/ C4	0.72, 1.26, 1.73	[12, 14, 27]
PETN[a]	1.73, 2.51	[12]
PETN[b]	2.01	[16]
HMX[a]	1.58, 1.91, 2.21, 2.57	[12]
HMX[b]	1.84	[16]
TNT[a]	1.44, 1.91	[12]
TNT[b]	1.7	[16]
TNT	5.6, 8.2, 9.1, 9.9	[20, 27]
NH_4NO_3	4, 7	[16, 22]
Drugs		
Methamphetamine	1.2, 1.7–1.8	[23]
MDMA	1.4, 1.8	[23]
Lactose α-monohydrate	0.54, 1.20, 1.38, 1.82, 2.54, 2.87, 3.29	[12]
Icing sugar	1.44, 1.61, 1.82, 2.24, 2.57, 2.84, 3.44	[12]
Co-codamol	1.85, 2.09, 2.93	[12]
Aspirin, soluble	1.38, 3.26	[12]
Aspirin, caplets	1.4, 2.24	[12, 23]
Acetaminophen	6.5	[19]
Terfenadine	3.2	[19]
Naproxen sodium	5.2, 6.5	[19]

[a] Samples are prepared as pellets using spectrographic-grade polyethylene.
[b] Samples are ordered as compressed pellets from Accurate Energetics LLC. All materials are in sensitized form (water-free).

Federici et al. Semicond. Sci. Technol. (2005)

Drugs in envelopes

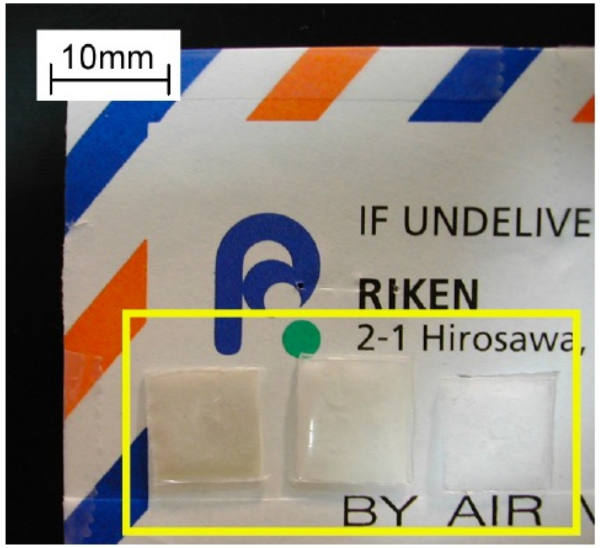


Fig. 2. View of the samples. The small polyethylene bags contain from left to right: MDMA, aspirin, and methamphetamine. The bags were placed inside the envelope during imaging. The area indicated by the yellow line represents the imaging target, 20×38mm in size. Since methamphetamine and aspirin are similar in appearance, we used a slightly longer bag for the latter to avoid confusion.

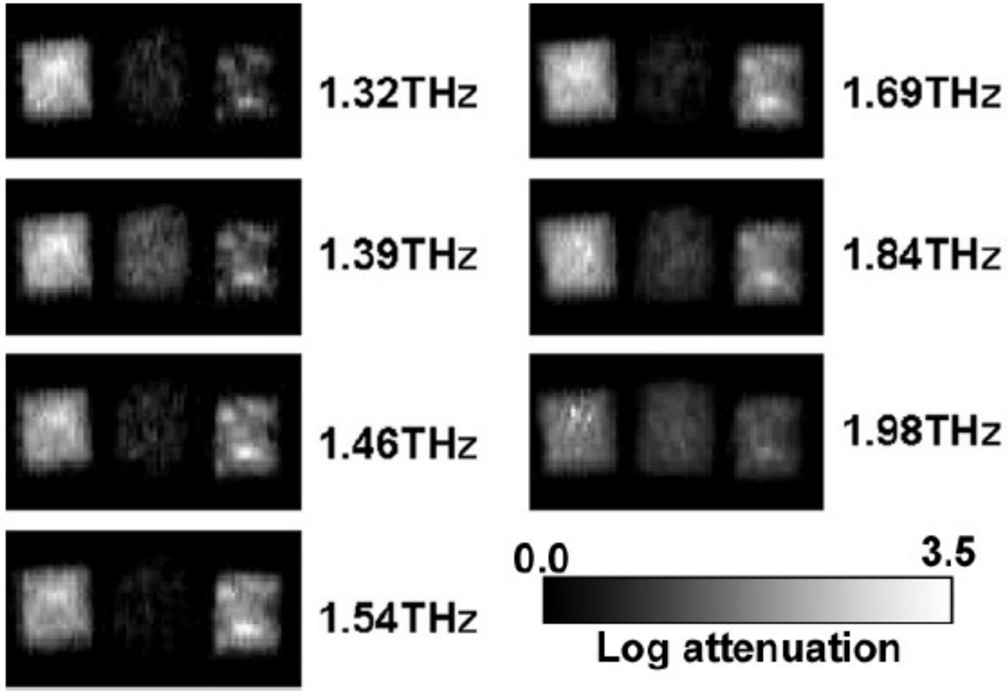


Fig. 3. Seven multispectral images generating a matrix [I].

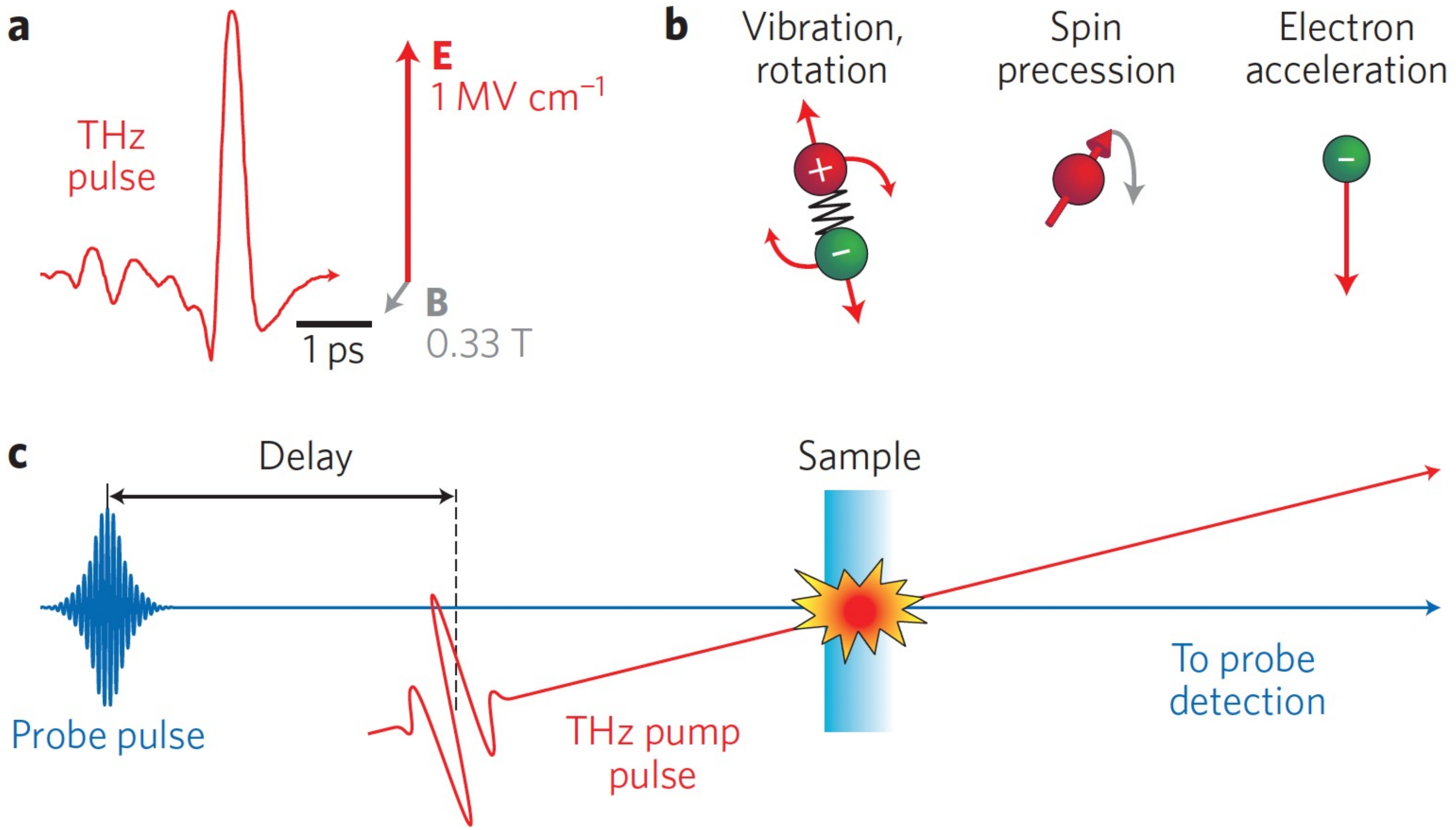
Kawase, Opt. Express (2003)

Hidden paint layers

(a) Image in the visible. (b) 50% visible, 50% THz image. (c) 100% THz image.

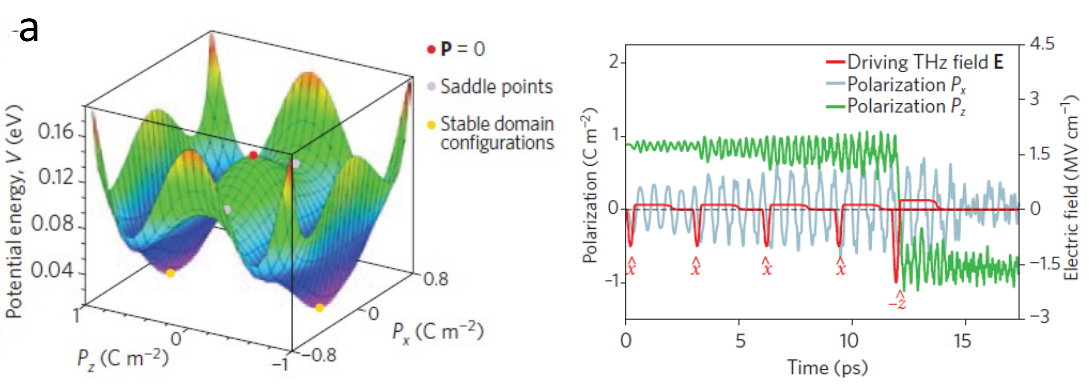
C. Seco-Martorell, V. López-Domínguez, G. Arauz-Garofalo, A. Redo-Sanchez, J. Palacios, and J. Tejada, "Goya's artwork imaging with Terahertz waves," Opt. Express 21, 17800-17805 (2013)

THz-pump optical-probe spectroscopy

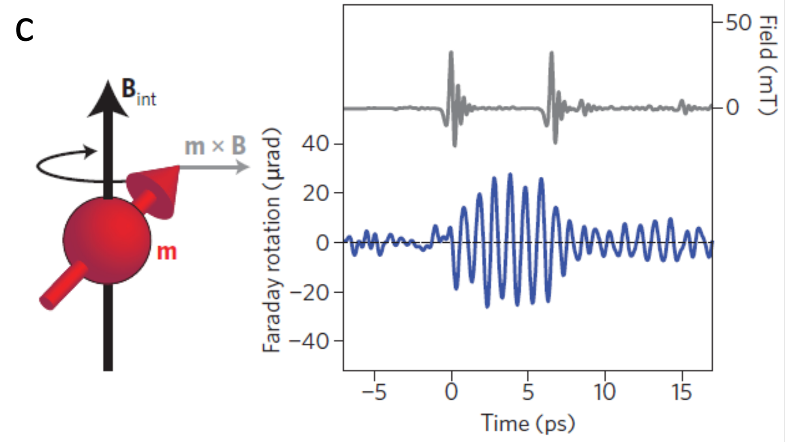


Kampfrath, T., Tanaka, K. & Nelson, K. Resonant and nonresonant control over matter and light by intense terahertz transients. *Nature Photon* **7**, 680–690 (2013).

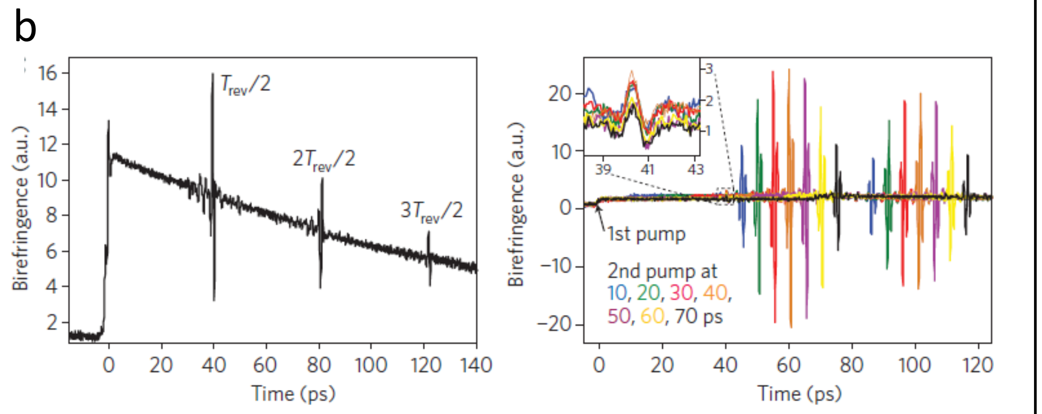
THz-pump optical-probe spectroscopy



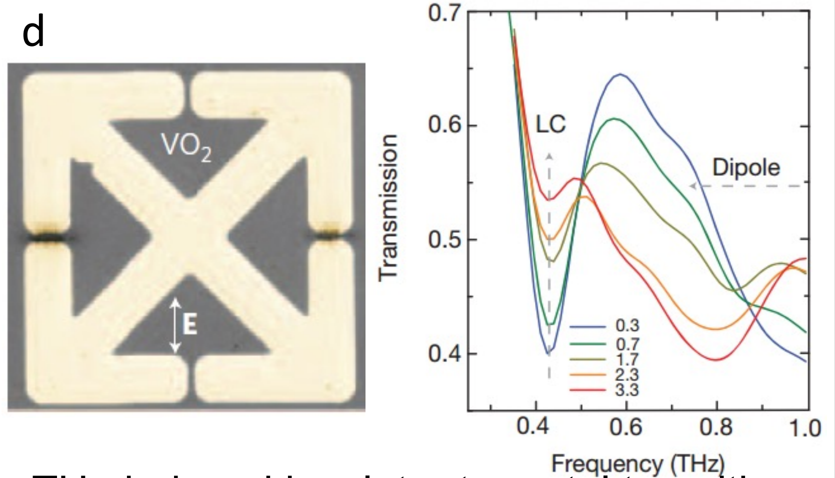
THz E field control of lattice vibration



THz B field control of spin precession



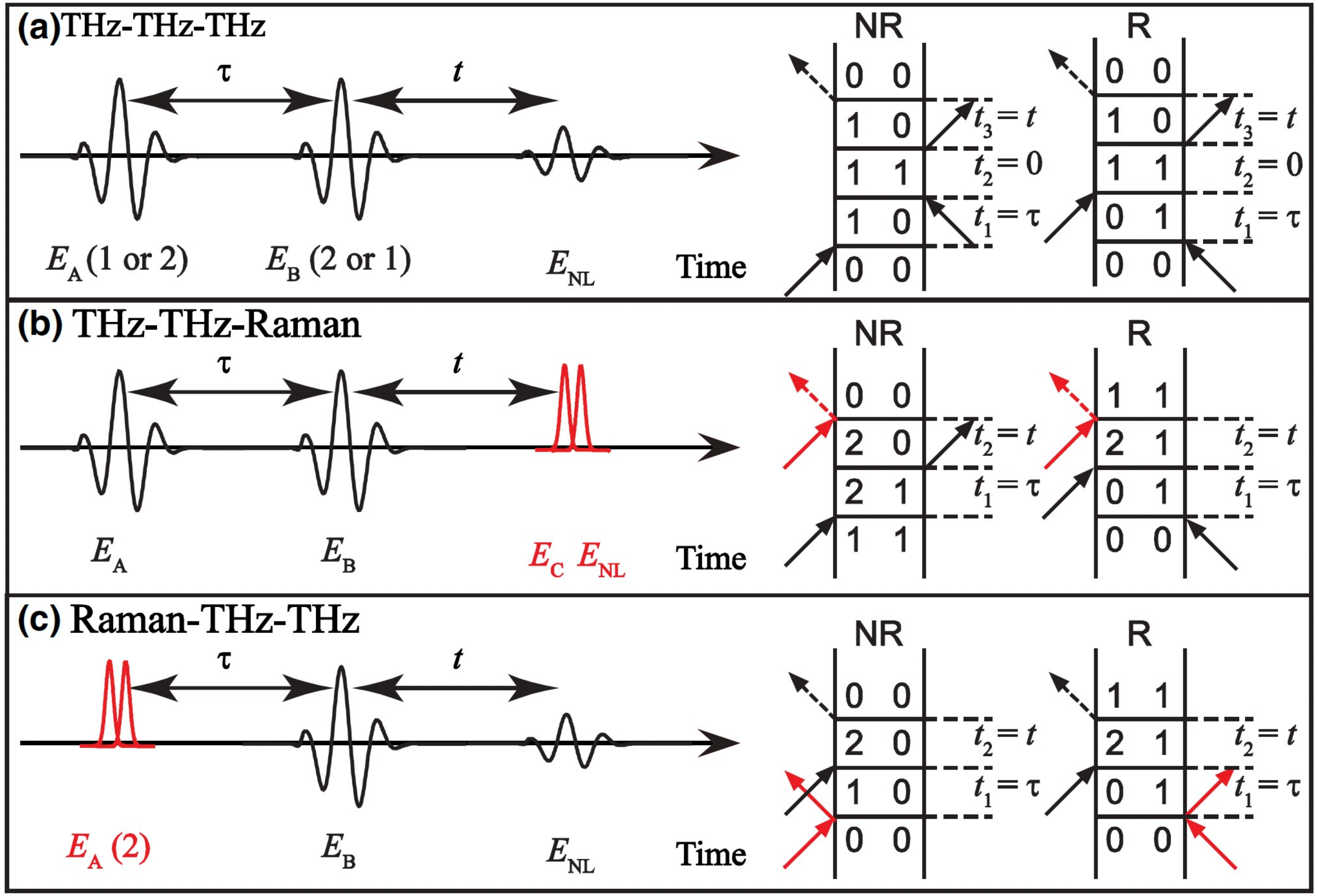
THz E field control of gas phase molecular alignment



THz-induced insulator to metal transition

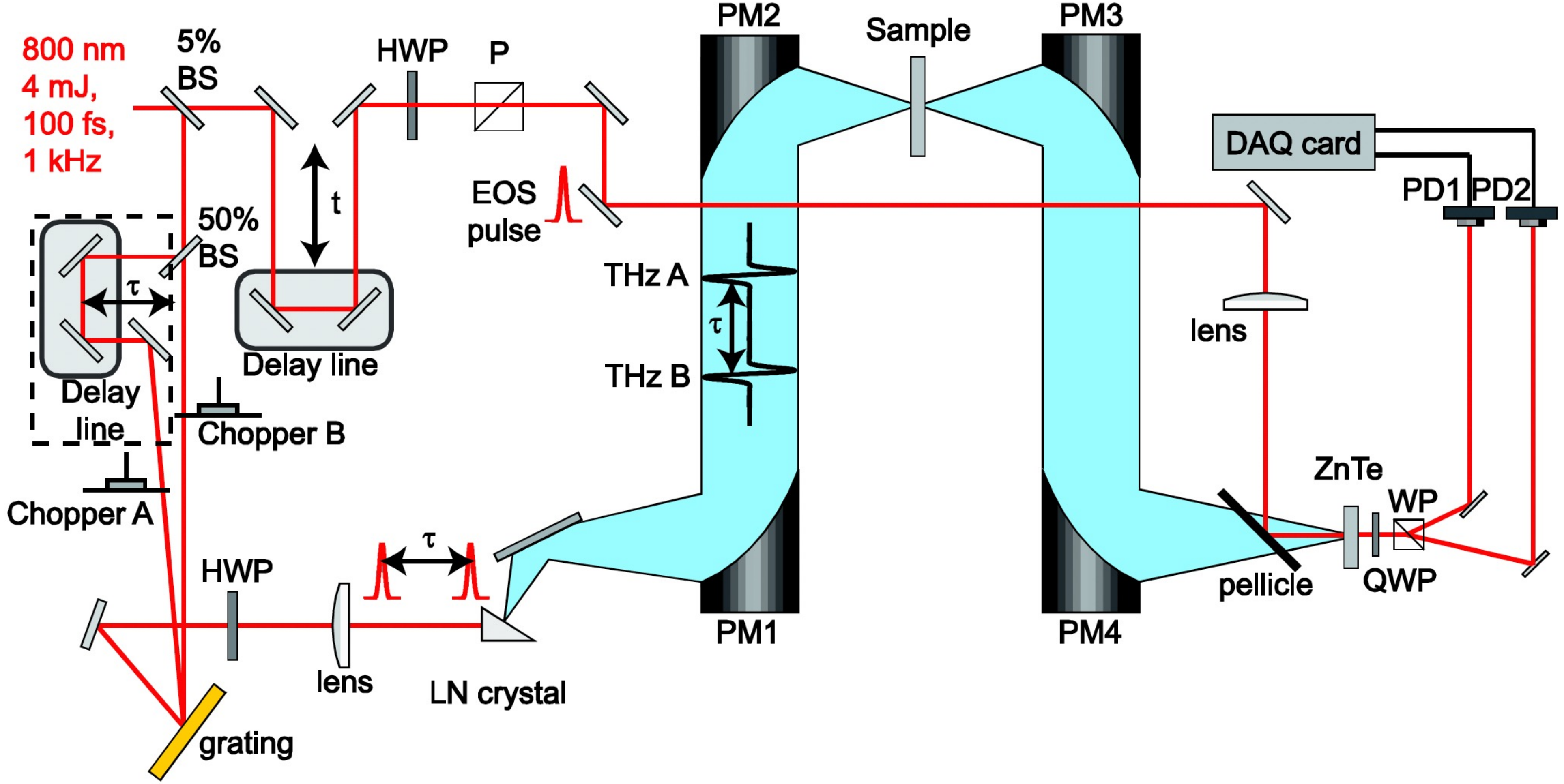
Kampfrath, T., Tanaka, K. & Nelson, K. Resonant and nonresonant control over matter and light by intense terahertz transients. *Nature Photon* **7**, 680–690 (2013).

2D THz and 2D THz-Raman spectroscopies



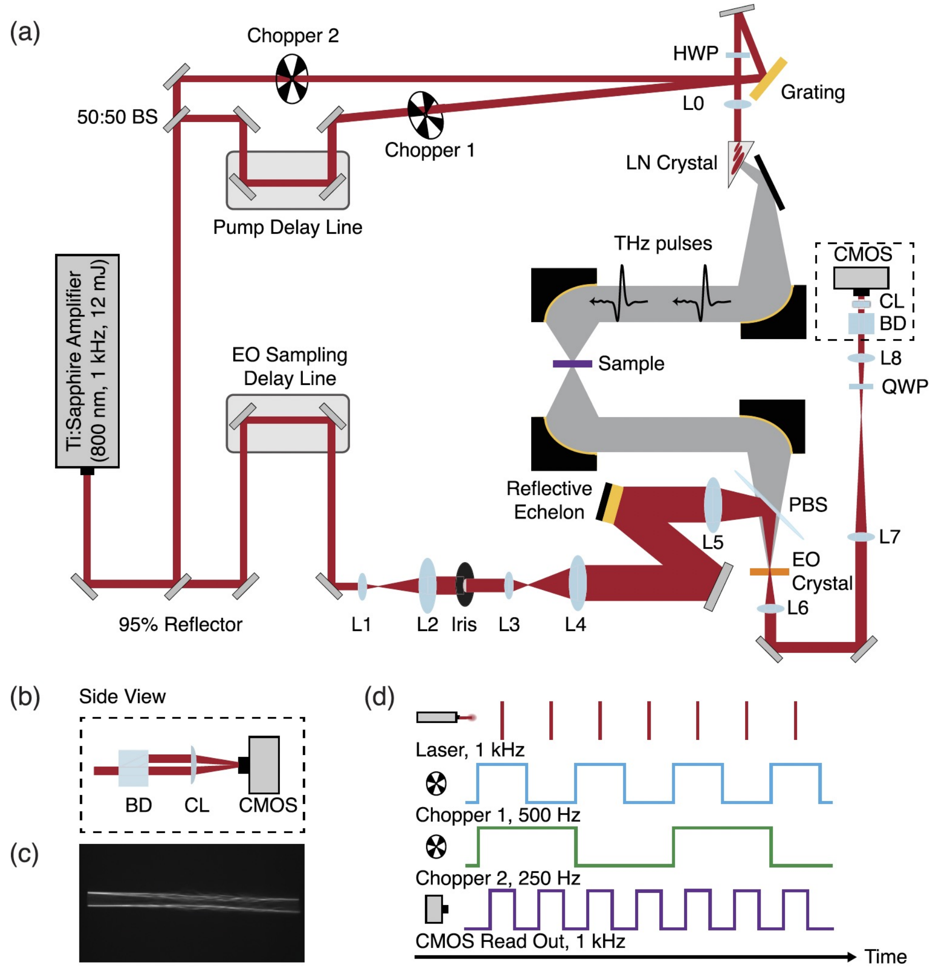
Lu, J., Li, X., Zhang, Y. *et al.* Two-Dimensional Spectroscopy at Terahertz Frequencies. *Top Curr Chem (Z)* **376**, 6 (2018).

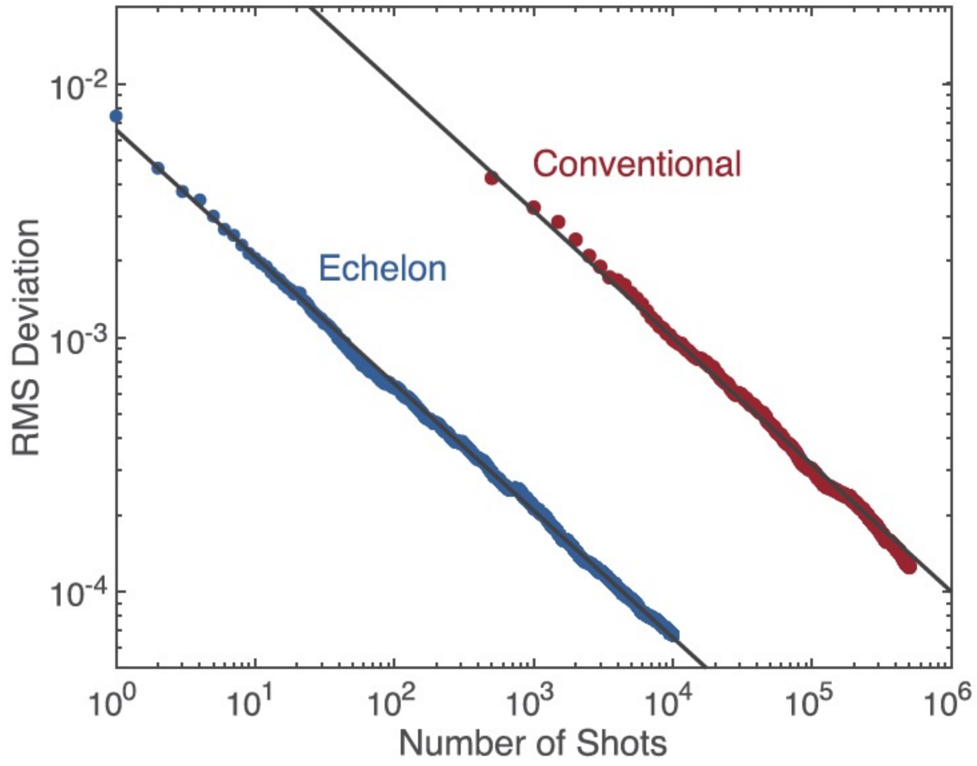
2D THz spectroscopy



Lu, J., Li, X., Zhang, Y. *et al.* Two-Dimensional Spectroscopy at Terahertz Frequencies. *Top Curr Chem (Z)* **376**, 6 (2018).

2D THz spectroscopy with single-shot detection

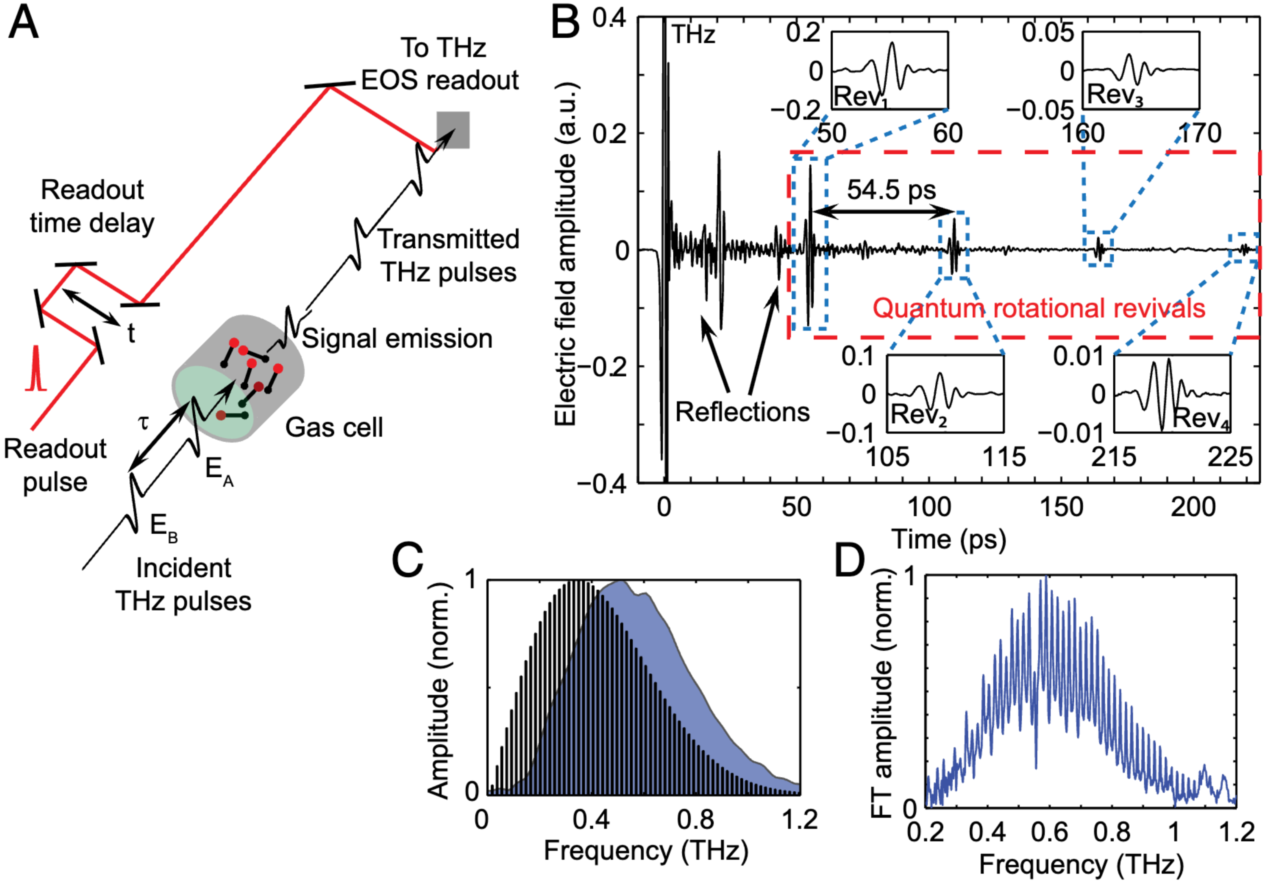


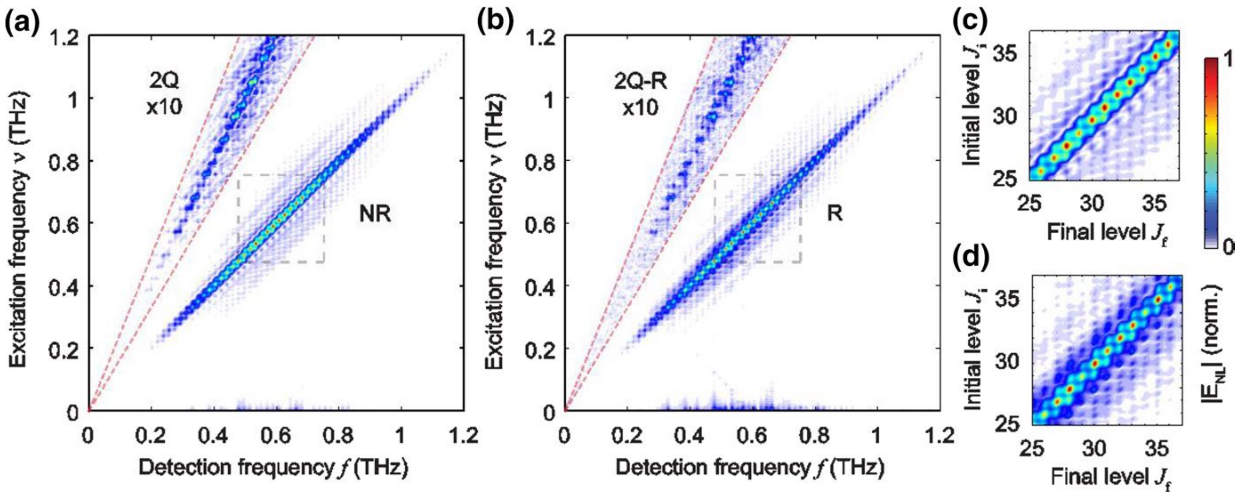


200-fold speed up in acquisitions

Frank Y. Gao, Zhuquan Zhang, Zi-Jie Liu, and Keith A. Nelson, "High-speed two-dimensional terahertz spectroscopy with echelon-based shot-to-shot balanced detection," Opt. Lett. 47, 3479-3482 (2022)

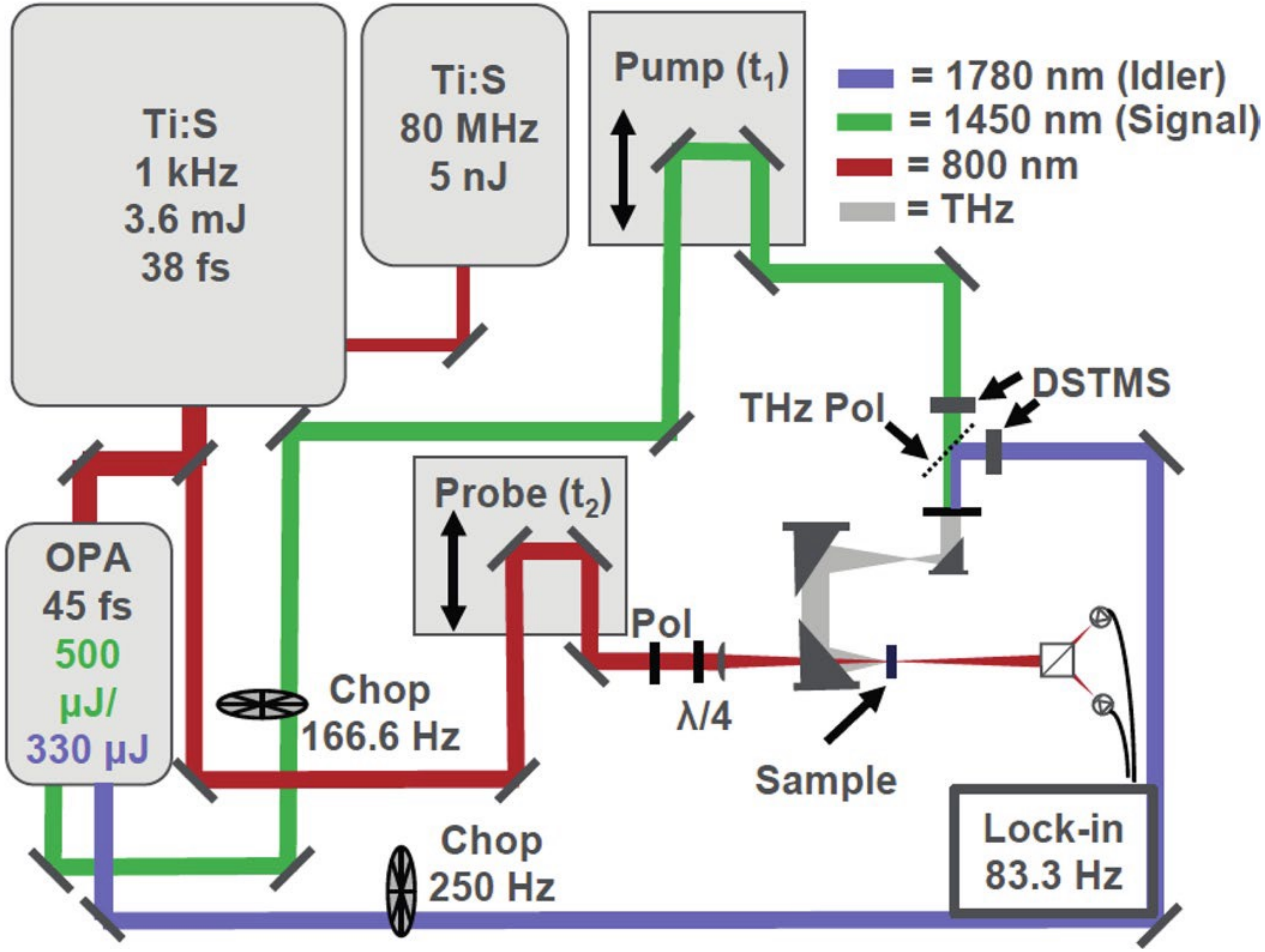
2D THz spectroscopy in gas





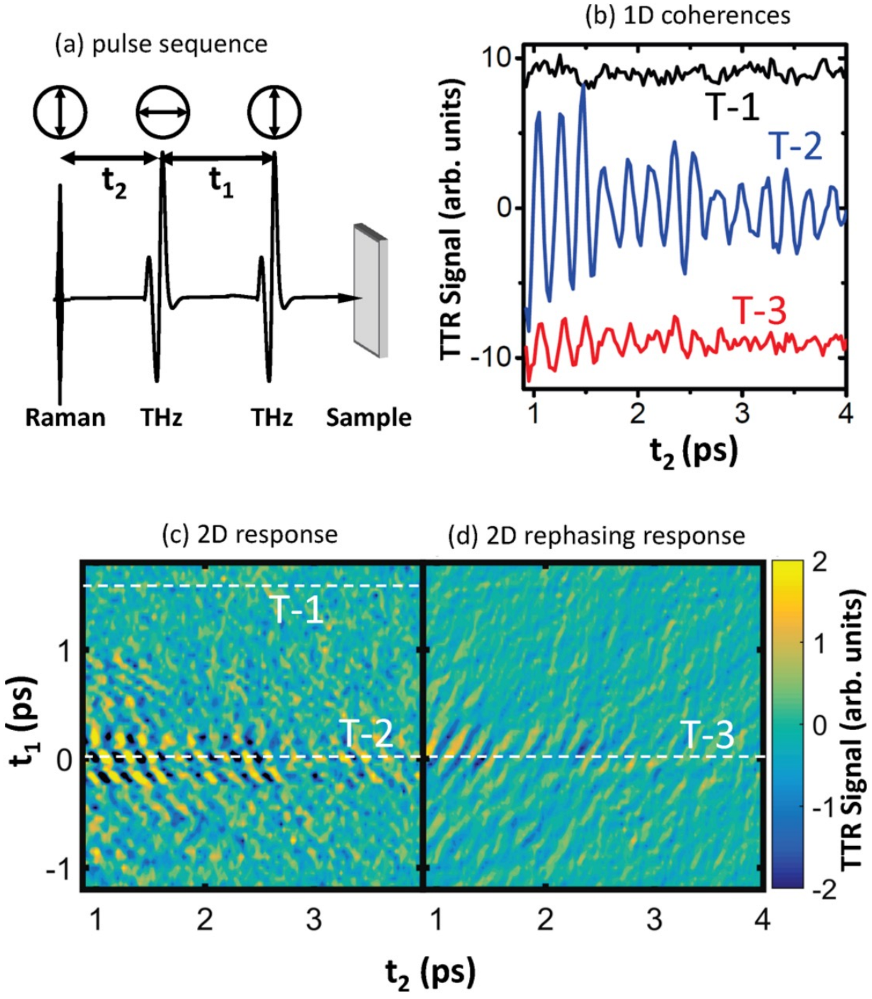
J. Lu, Y. Zhang, H.Y. Hwang, B.K. Ofori-Okai, S. Fleischer, & K.A. Nelson, Nonlinear two-dimensional terahertz photon echo and rotational spectroscopy in the gas phase, Proc. Natl. Acad. Sci. U.S.A. 113 (42) 11800-11805 (2016).

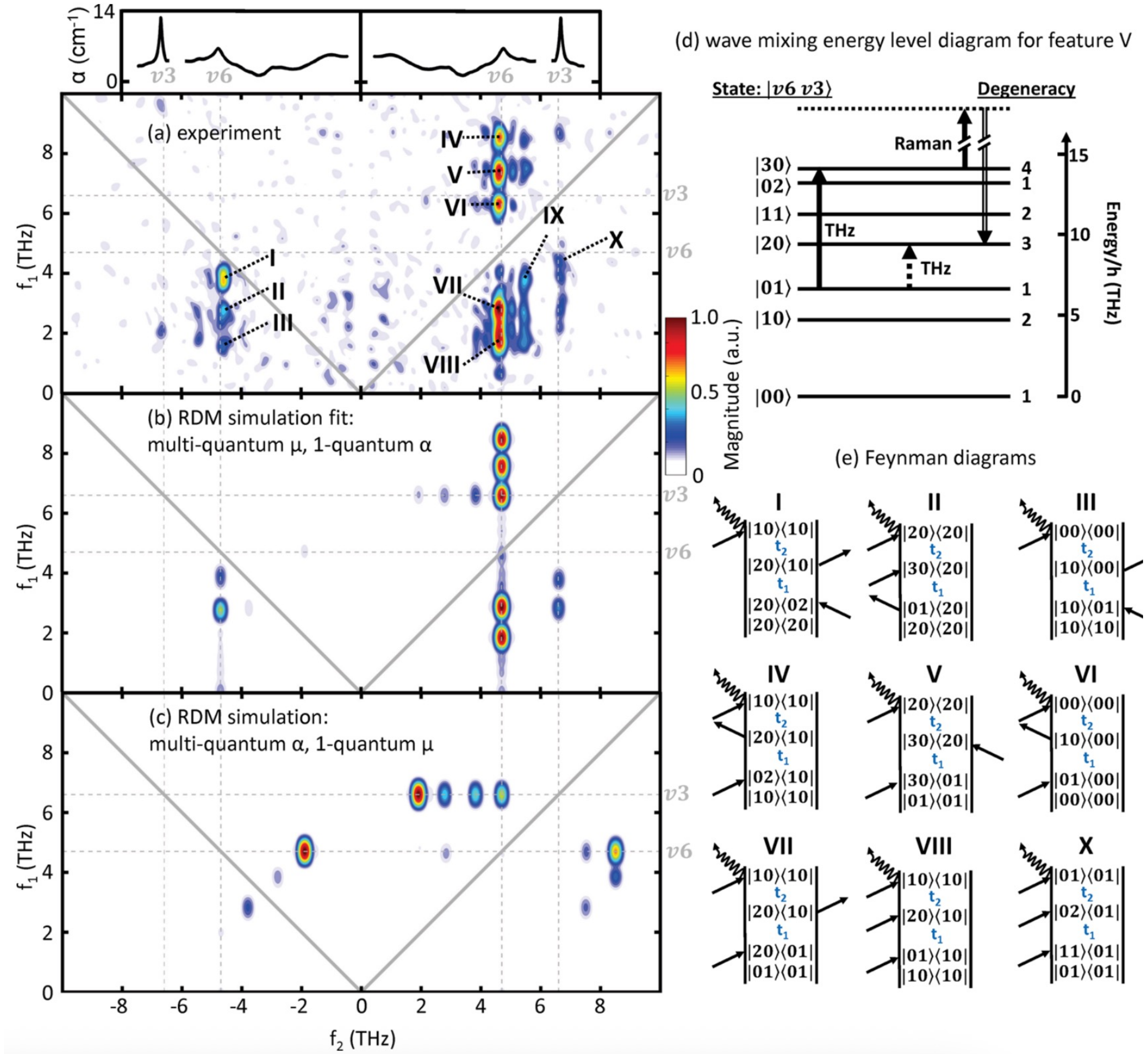
THz-THz-Raman spectroscopy



J. Phys. Chem. Lett. 2017, 8, 18, 4640–4644

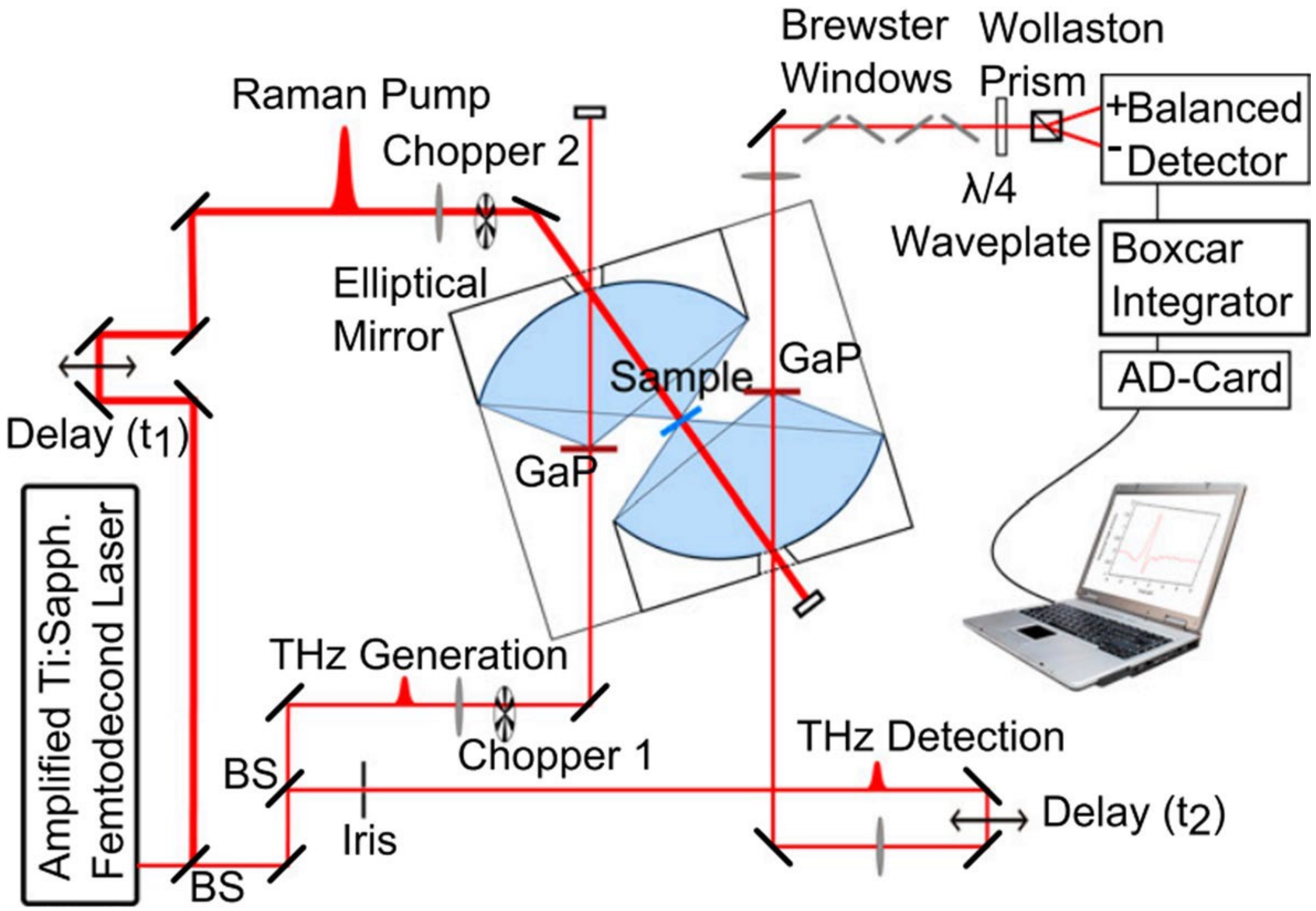
THz-THz-Raman spectroscopy of Bromoform





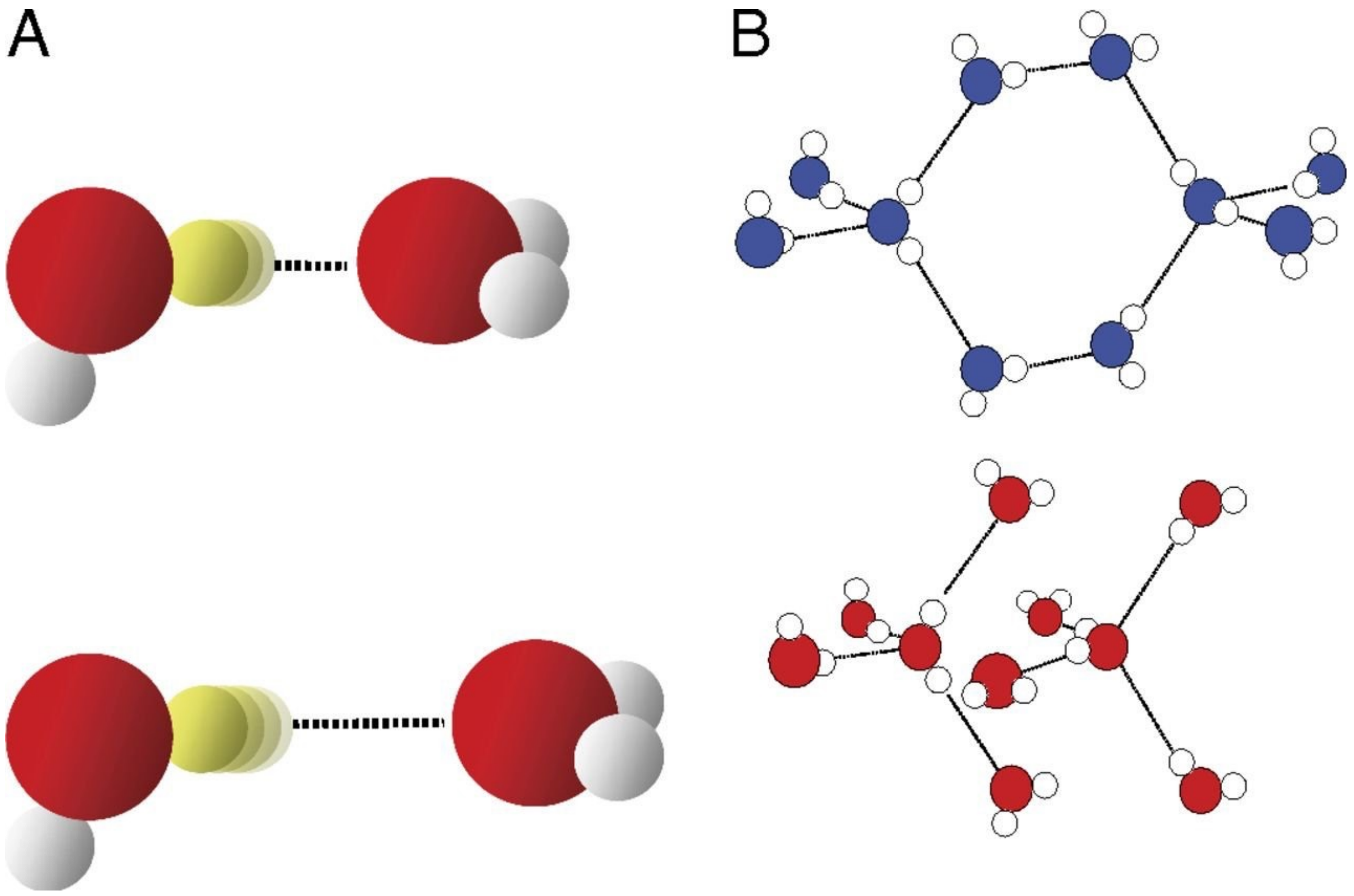
J. Phys. Chem. Lett. 2017, 8, 18, 4640–4644

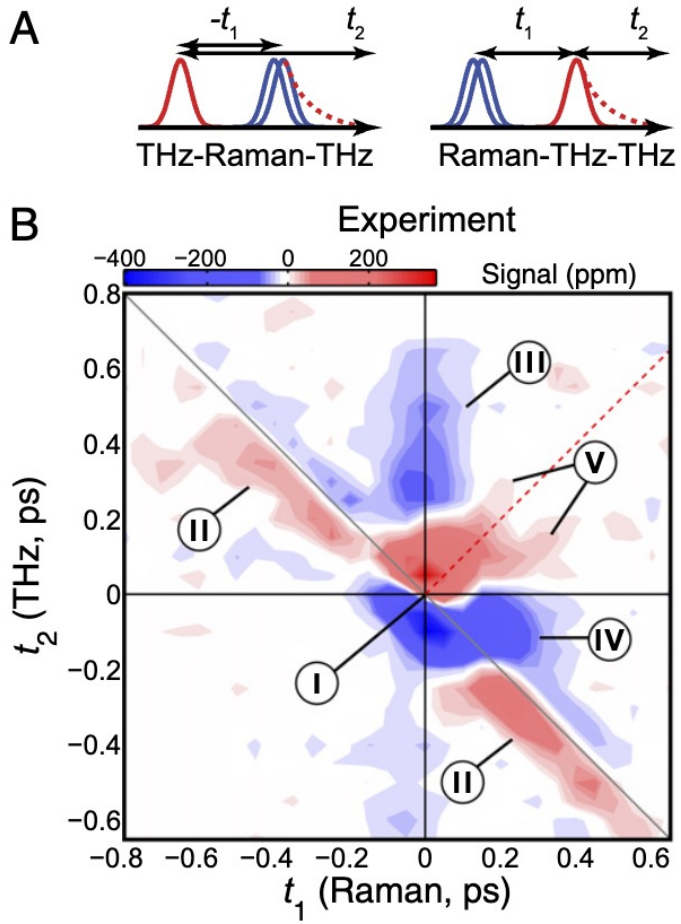
Raman-THz-THz spectroscopy



J. Savolainen, S. Ahmed, & P. Hamm, Two-dimensional Raman-terahertz spectroscopy of water, Proc. Natl. Acad. Sci. U.S.A. 110 (51) 20402-20407 (2013).

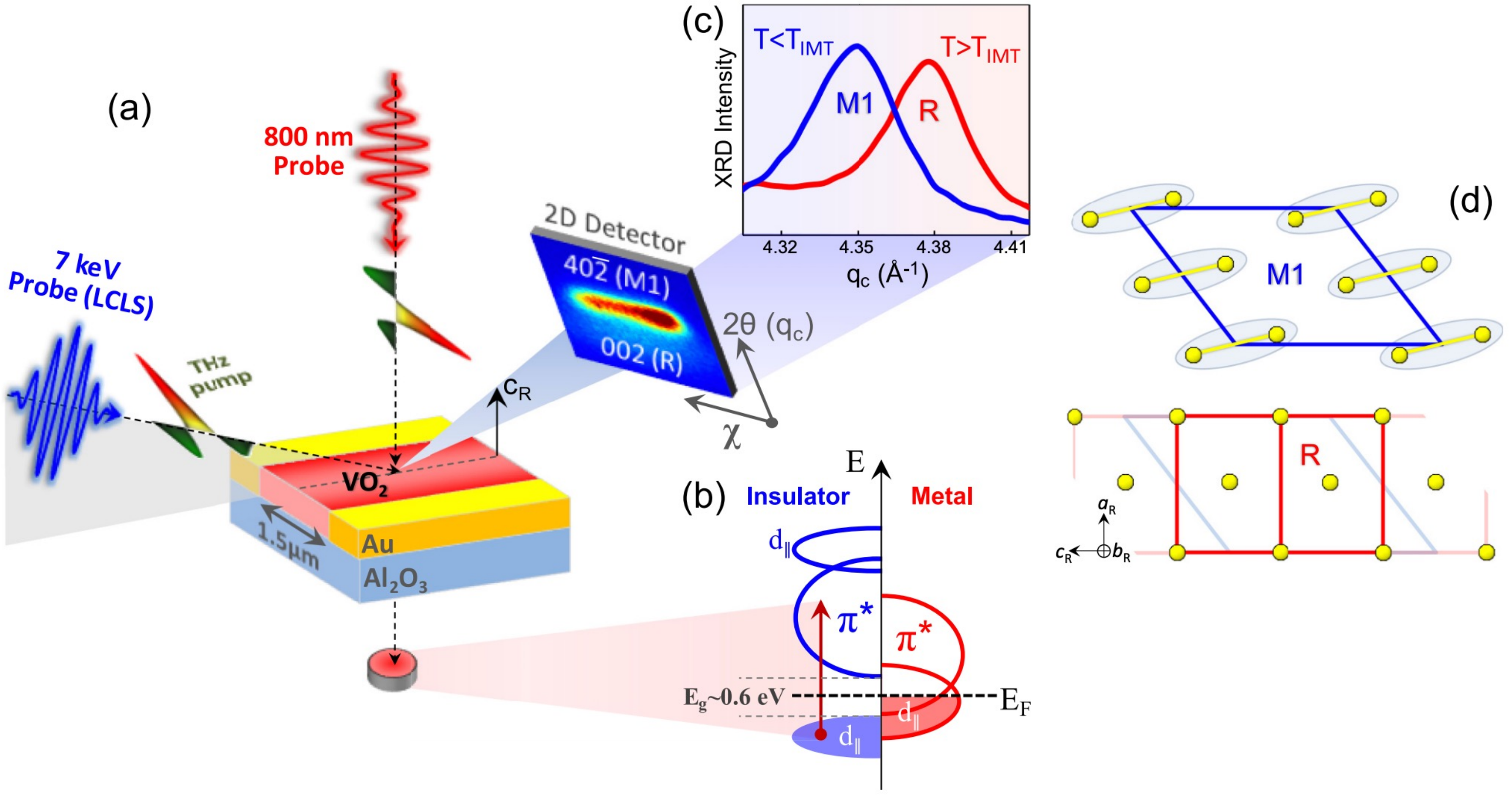
Raman-THz-THz spectroscopy of water

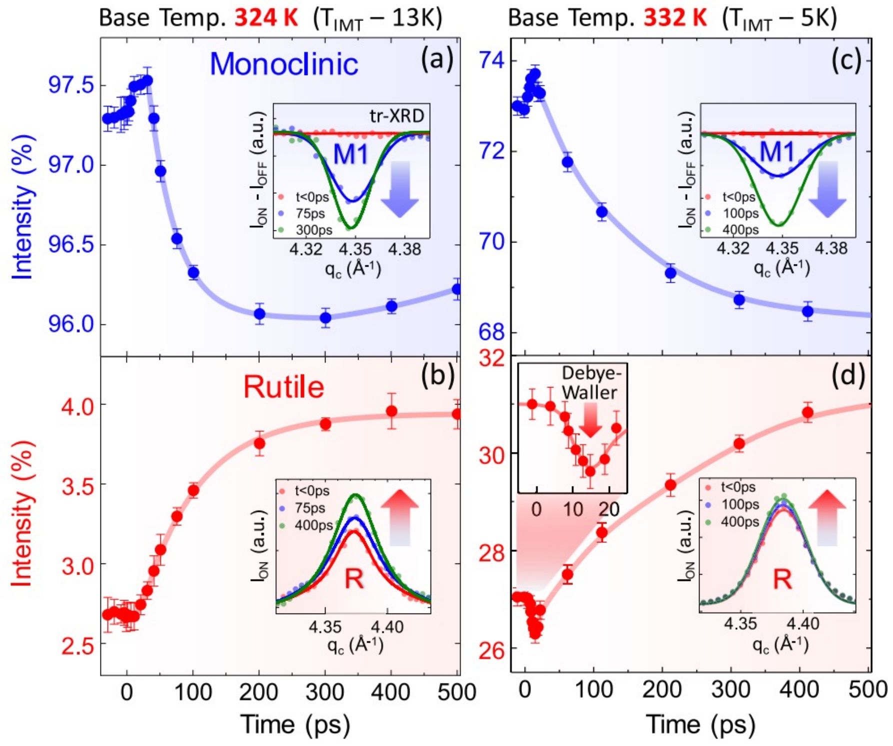




J. Savolainen, S. Ahmed, & P. Hamm, Two-dimensional Raman-terahertz spectroscopy of water, Proc. Natl. Acad. Sci. U.S.A. 110 (51) 20402-20407 (2013).

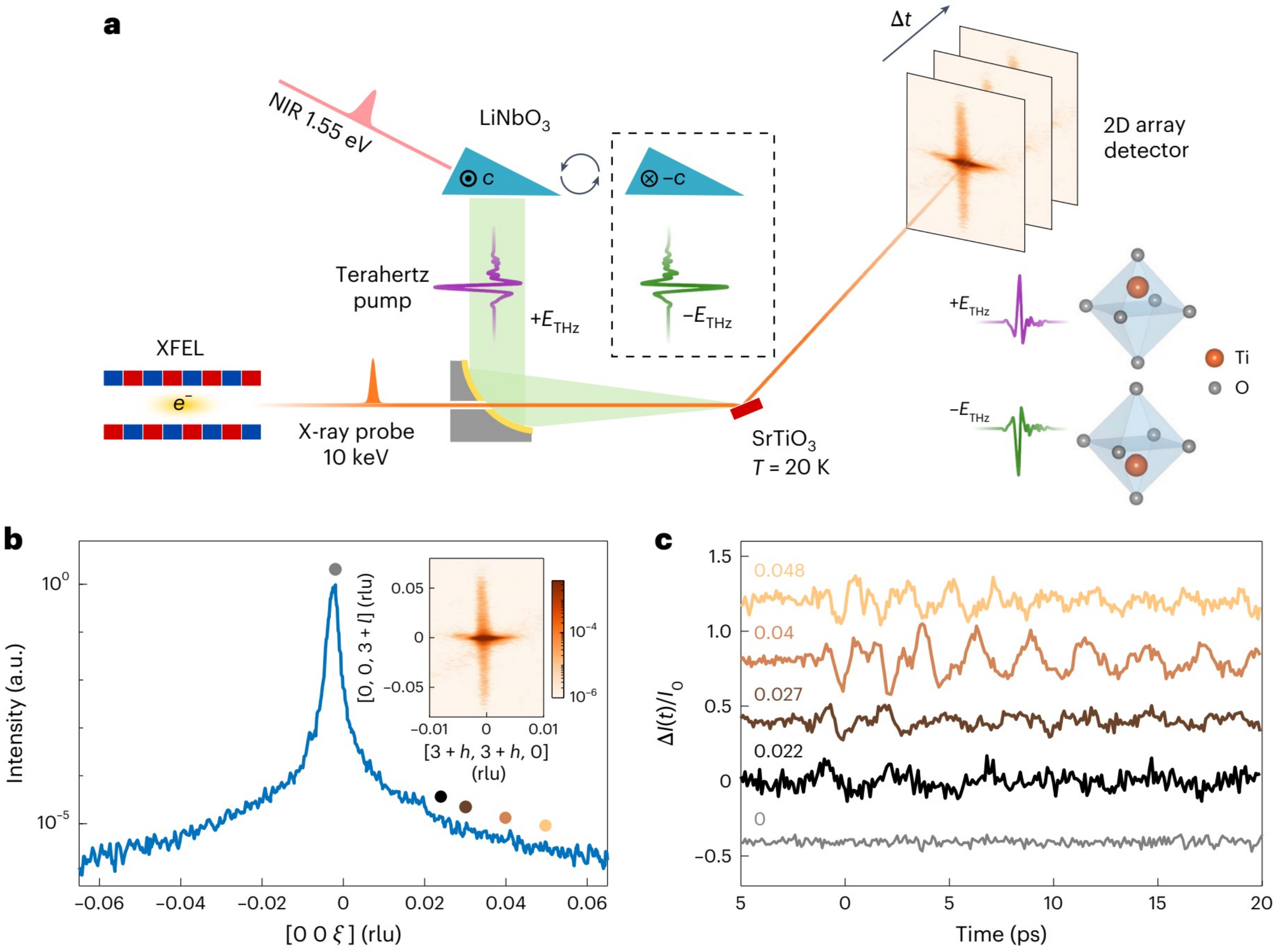
THz-pump X-ray-probe spectroscopy in VO_2

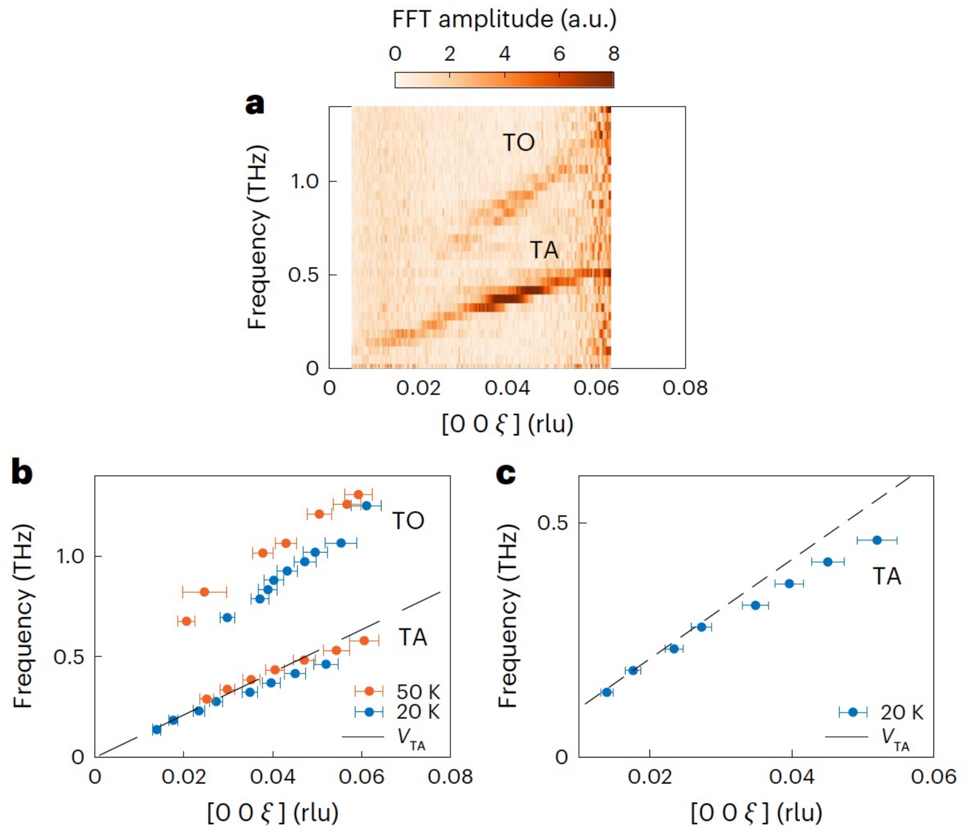




Phys. Rev. B **98**, 04510

THz-pump X-ray-probe spectroscopy in STO





Orenstein, G., Krapivin, V., Huang, Y. *et al.* Observation of polarization density waves in $SrTiO_3$. *Nat. Phys.* **21**, 961–965 (2025).

Thank you