# Ch.1
# Terahertz Time-Domain Spectrometer

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# Contents

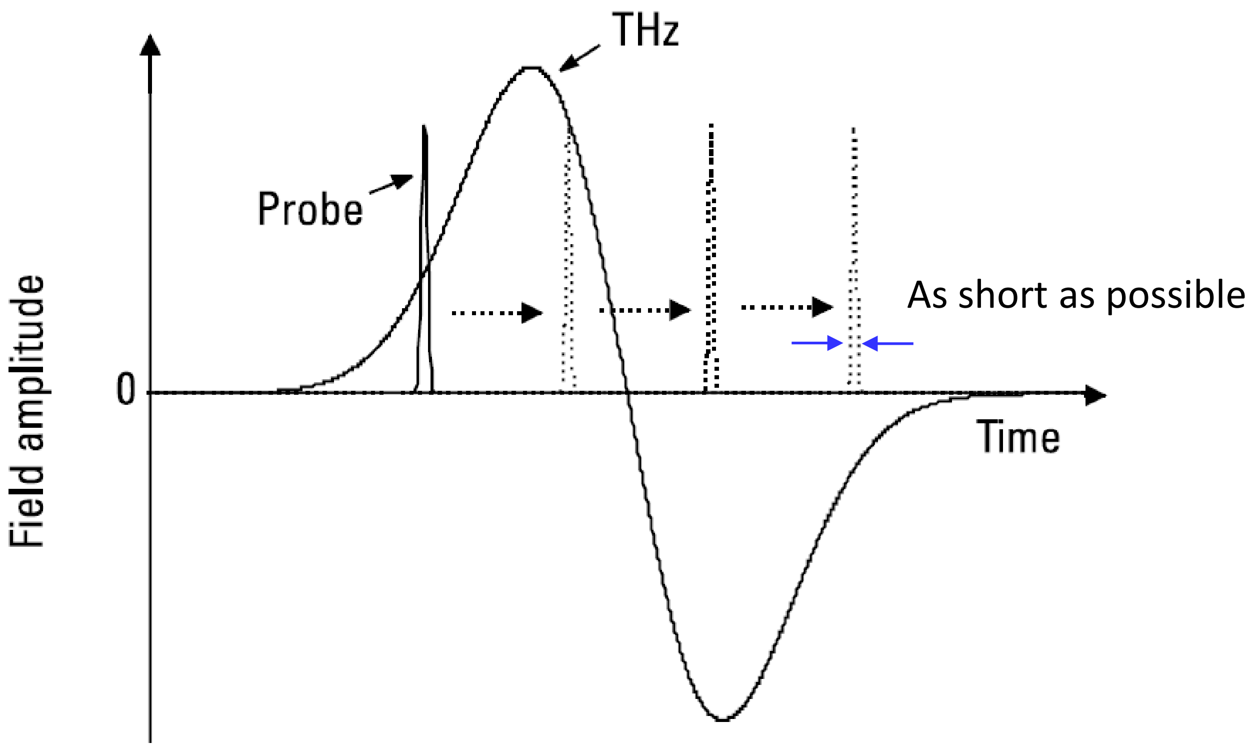
# Pulsed Terahertz Time-Domain Spectrometers

# 1.1 Principles of Operation

Single-cycle optical pusle → Terhertz beam
→ Coherent and Broadband

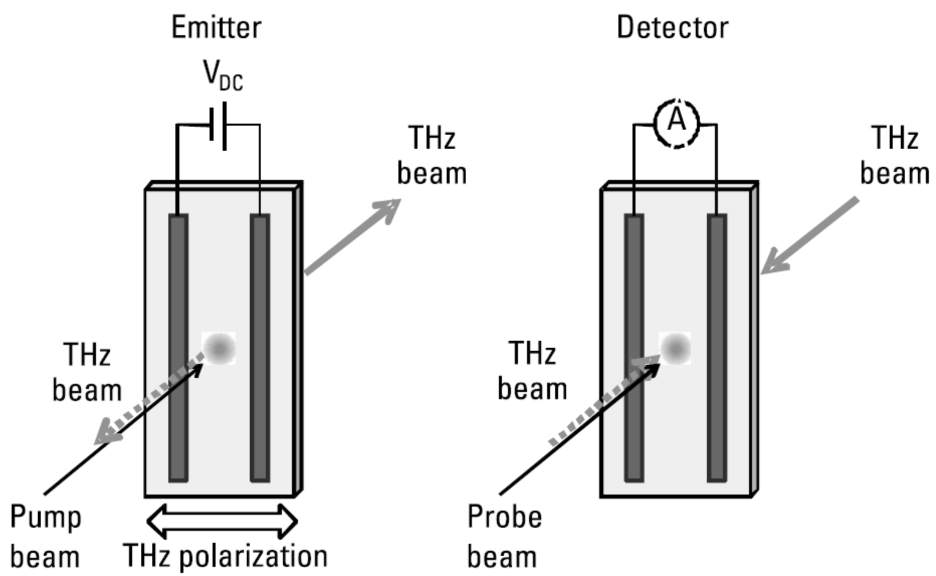
Closed-loop pump-probe configuration → High signal-to-noise ratio and the Dynamic range

# 1.1 Principles of Operation




$$Signal(t_0) \propto \int_{-\infty}^{\infty} I_{\text{probe}}(t - t_0) E_{THz}(t) dt$$

# 1.2 Photoconductive Emitters and Detectors



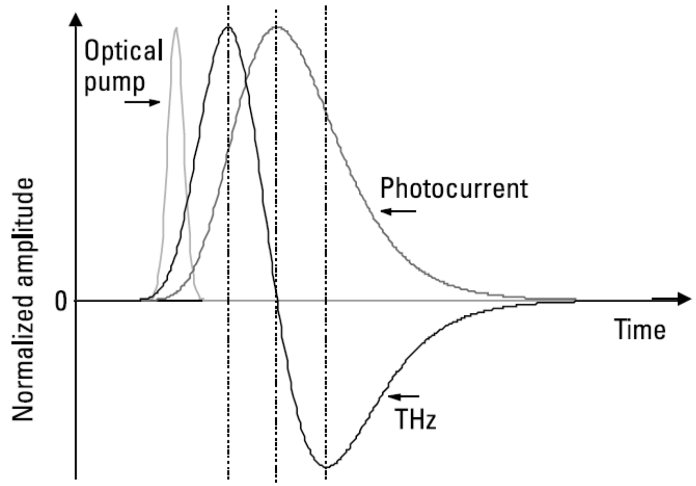

Ti-sapphire (800nm) ➔ 1.55ev
GaAs ➔ 1.42eV

-> generate carriers

$$E_{THz}(r,t) = \frac{l_e}{4\pi\epsilon_0 c^2 r}\frac{\partial J(t)}{\partial t}\sin\theta \;\propto \frac{\partial J(t)}{\partial t}$$

$$J_{PC} = q_C N_C v_C \;\propto I_{opt} V_{DC}$$

# 1.2 Photoconductive Emitters and Detectors




- The rise time of the photocurrent: the pump laser pulse length
- The fall time of the photocurrent: 1. the pulse length, 2. the semiconductor carrier lifetime, and 3. the time it takes for carrier to be swept out of the active region by the bias field

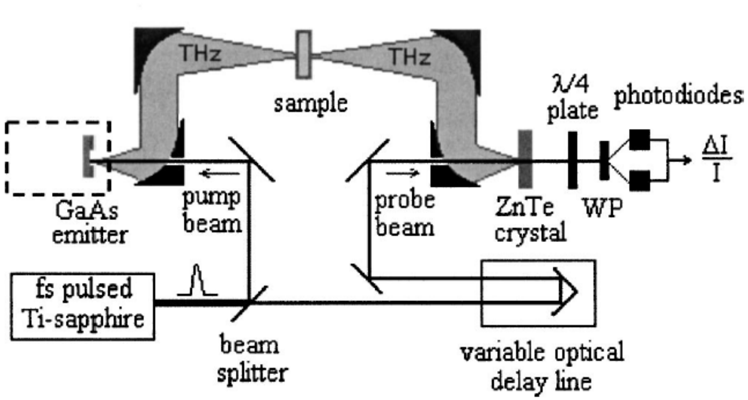
$$J_{THz}(t_0) = \int_{-\infty}^{t_0} \sigma_{PC}(t_0 - t) E_{THz}(t) dt$$

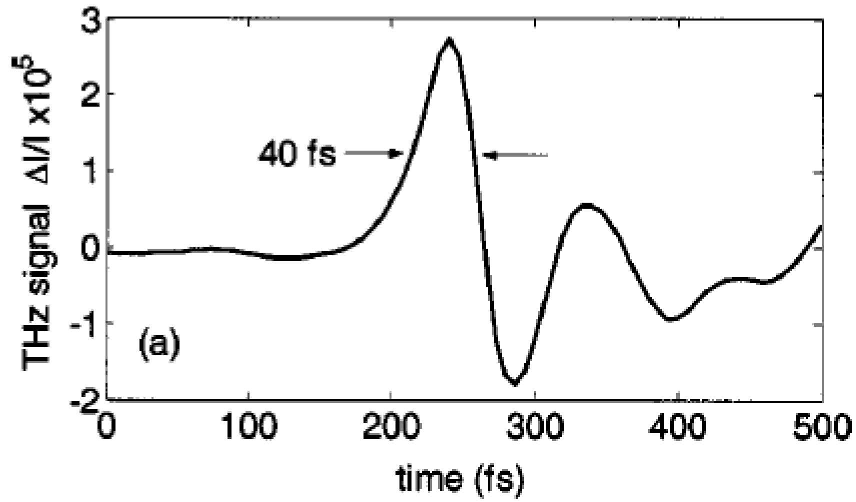
Emitter material

Mira
- Large optical absorption coefficient
- High optical damage threshold
- High breakdown voltage

Sakai
- Subpicosecond carrier lifetime
- Relativity high carrier mobility
- High breakdown fileds

# 1.2 Photoconductive Emitters and Detectors



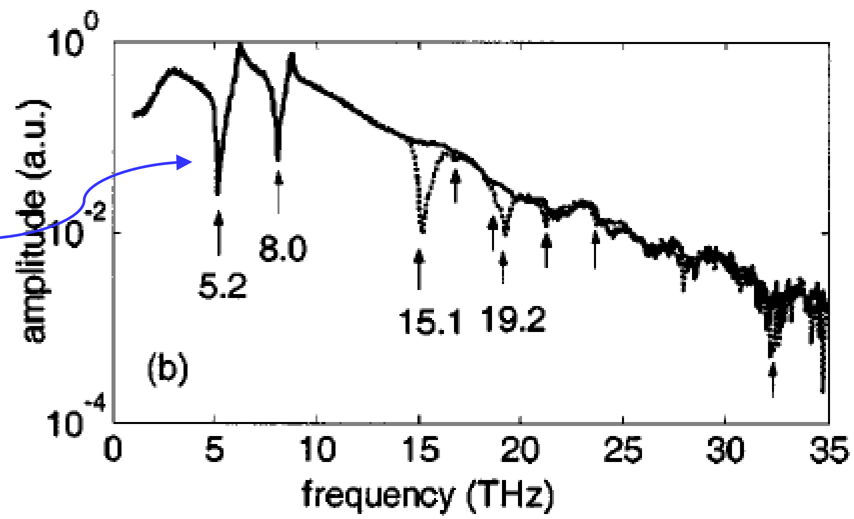




ZnTe detector

➔ (TO phonon energy: 22 meV = 5.3THz)

LT-GaAs

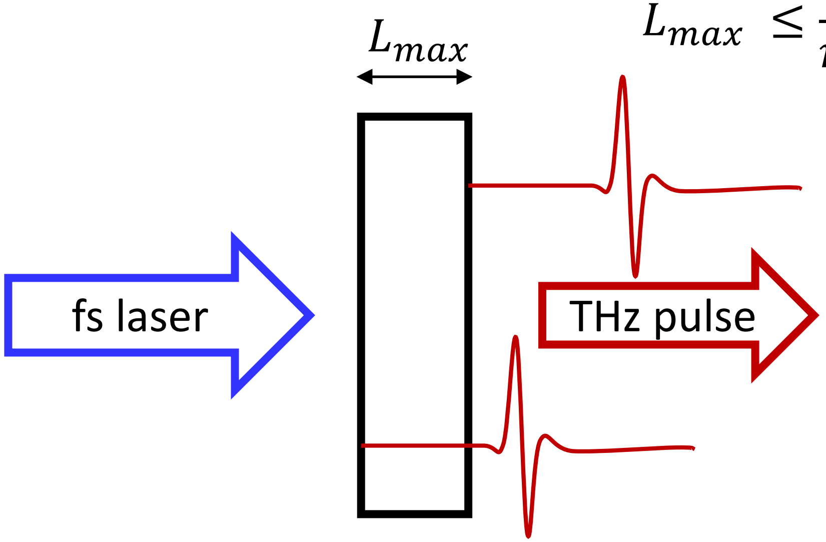
➔ (TO phonon energy: 33 meV = 8.0THz)




Shen, Y. C., et al., "Ultrabroadband Terahertz Radiation from Low-Termperature-Grown GaAs Photoconductive Emitters," *Appl. Phys. Lett.*, Vol. 83, 2003.

# 1.3 Optical Rectification

$$L_{max} \leq \frac{ct_{pump}}{n_{THz} - n_{pump}}$$

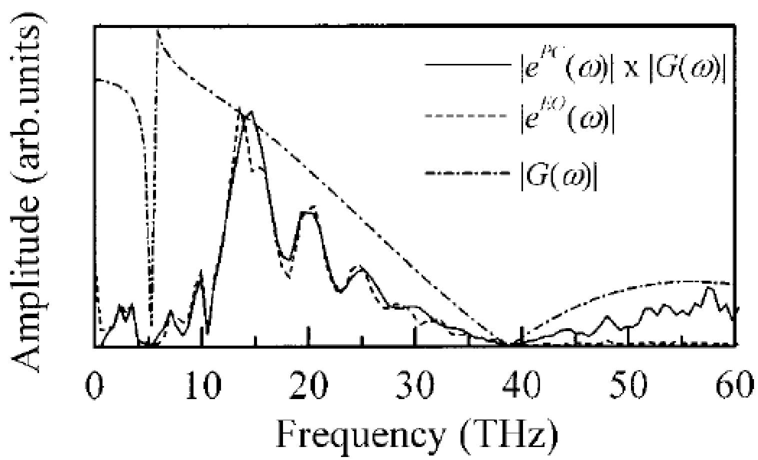


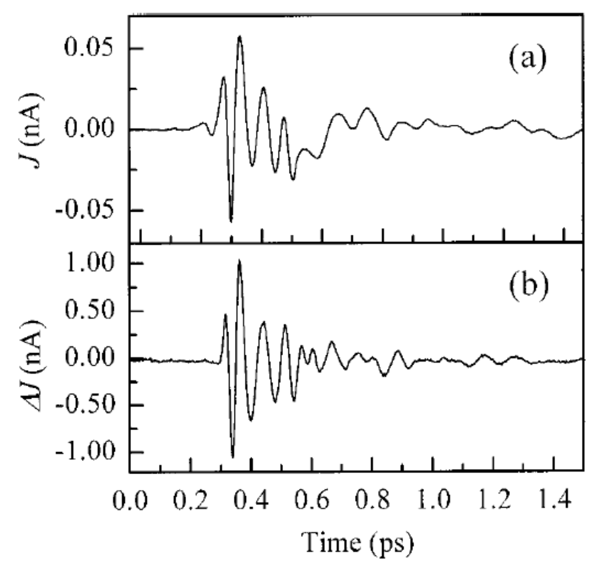

Non-linear crystal

Non-linear crystal: ZnTe ccrystal

➔ Absortion (phonon): 5.3, 3.5, 1.5 THz

(TI-sapphire, 800nm)

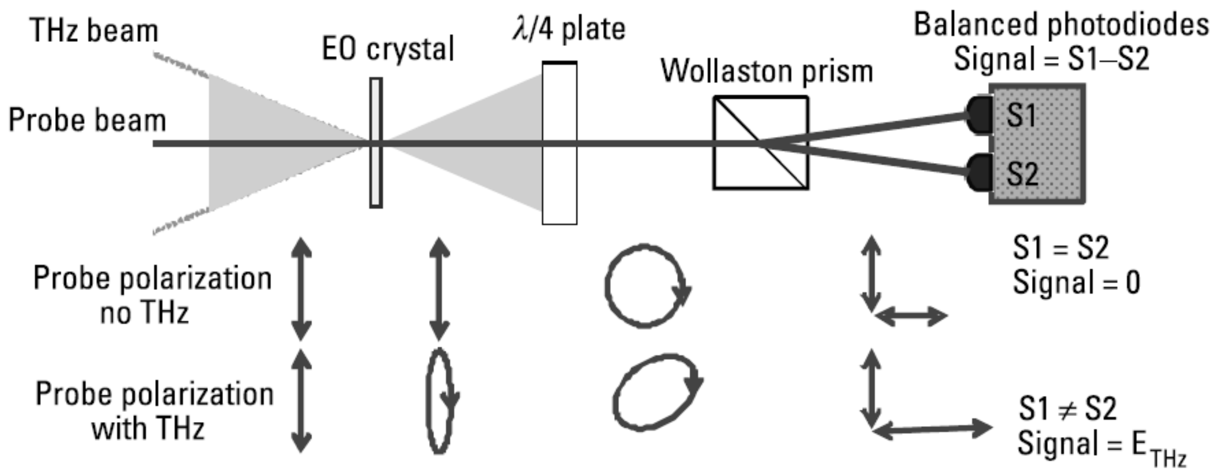



Kono, S., M. Tani, and K. Sakai, “Ultrabroadabnd Photoconductive Detection: Comparison with Free-SpaceElectro-Optic Sampling,” *Appl. Phys. Lett.*, Vol. 79, 2001.

# 1.4 Electro-Optic Detection

Electro-optic detection relies on the Pockels effect where an electric field gives rise to birefringence in an optical material.



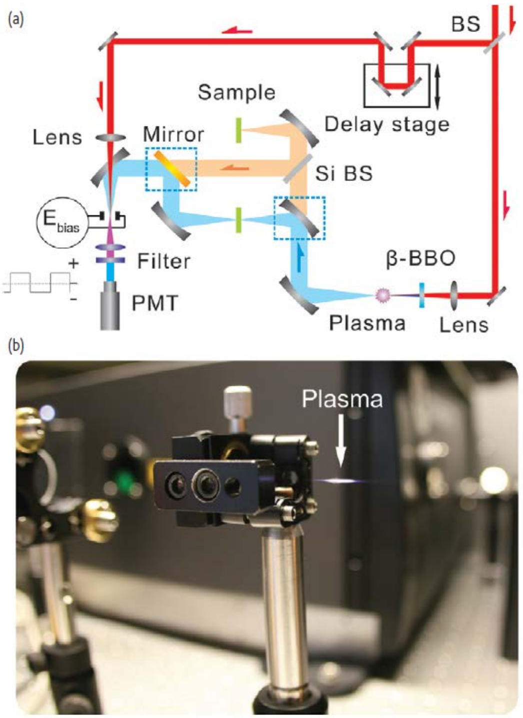

$$\frac{\Delta I}{I} = \frac{1}{2}(1+\sin\Delta\varphi) - \frac{1}{2}(1-\sin\Delta\varphi) = \sin\Delta\varphi \approx \Delta\varphi \qquad \Delta\varphi = \frac{2\pi L}{\lambda_{\text{probe}}} n_{\text{probe}}^3 r_{\text{eff}} E_{\text{THz}}$$

Advantages

- Easier alignment, lower sensitivity to probe beam pointing
- No need microfabricated highly specialized semiconductor device
- Simpler electronics

# 1.5 Terahertz Air-Based Coherent Detection

Terahertz air-based coherent detection (THz-ABCD) uses ionized air as a medium for ultra-broadband terahertz generation and detection




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

$$I_{2\omega}(t_0) \propto 2\left[\chi^{(3)} E_{\omega}^{2}(t)\right]^{2} E_{\text{bias}} E_{\text{THz}}(t - t_0)$$

➔ 3-order optical nonlinearlity in plasma

Ti-sapphire (65 fs, 800 nm)

Four-Wave Rectification (FWR) method

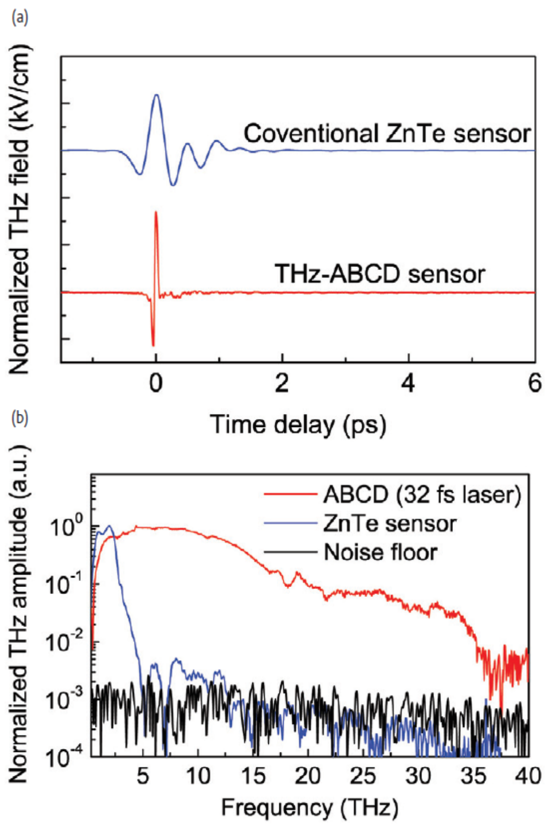
➔ β-BBO lens fouce 150μJ of energy

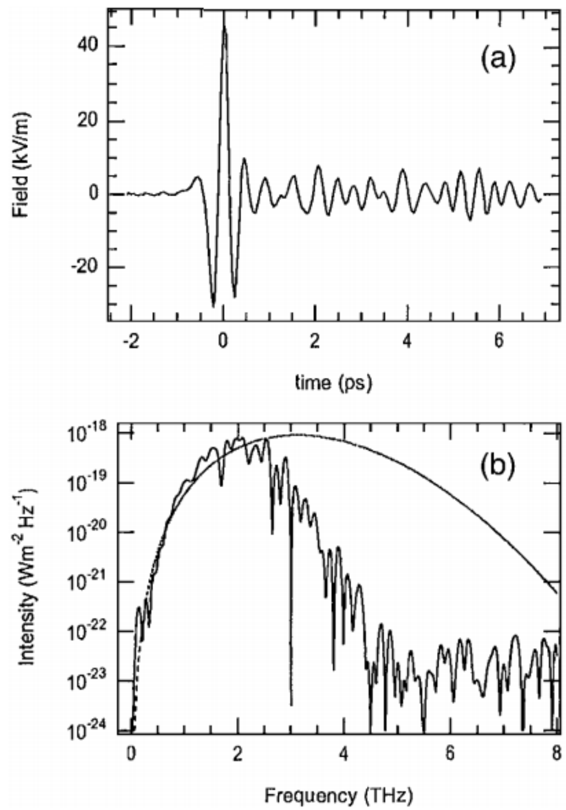
➔ The peak optical intensity: $5 \times 10^{14}\ \mathrm{W/cm^2}$


Clough, B., J. Dai, and X. –C. Zhang, "Laser Air Photonics: Beyond the Terahertz Gap," *Mater. Today*, Vol. 15, 2012.

D. J. Cook and R. M. Hochstrasser, "Intense terahertz pulses by four-wave rectification in air," *Opt. Lett*. 25, 1210-1212 (2000)

# 1.5 Terahertz Air-Based Coherent Detection

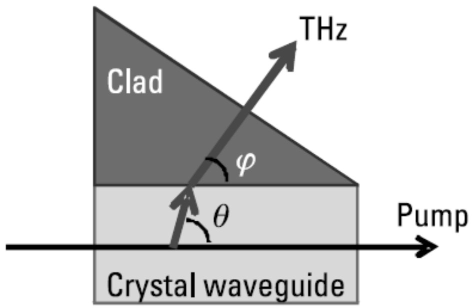


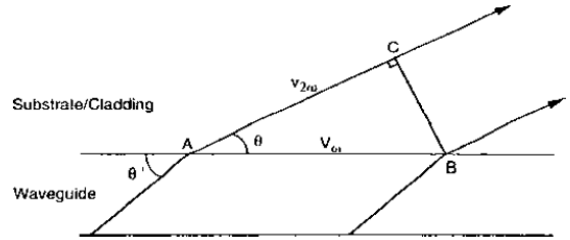




The requirement for an amplified ultrafast laser as a pump source and issues arising from working with plasma

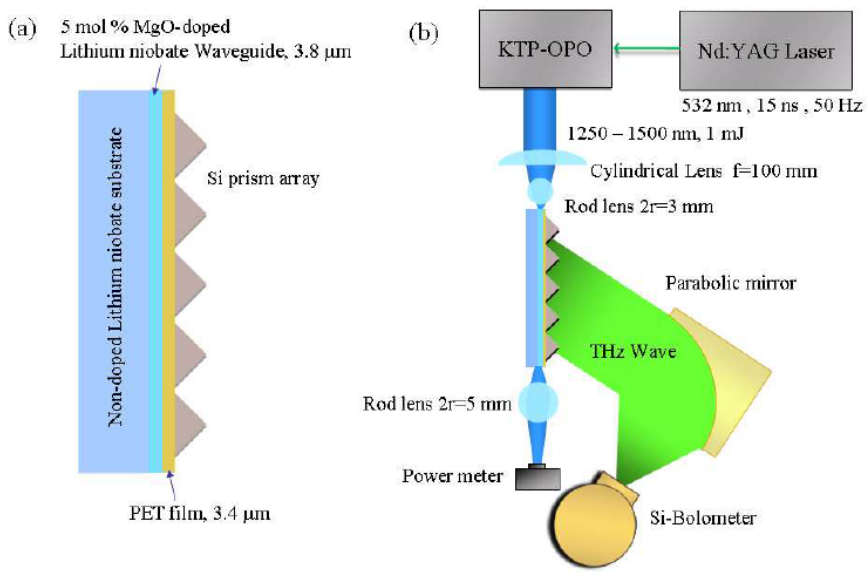

Clough, B., J. Dai, and X. –C. Zhang, “Laser Air Photonics: Beyond the Terahertz Gap,” *Mater. Today*, Vol. 15, 2012.
D. J. Cook and R. M. Hochstrasser, "Intense terahertz pulses by four-wave rectification in air," *Opt. Lett.* 25, 1210-1212 (2000)

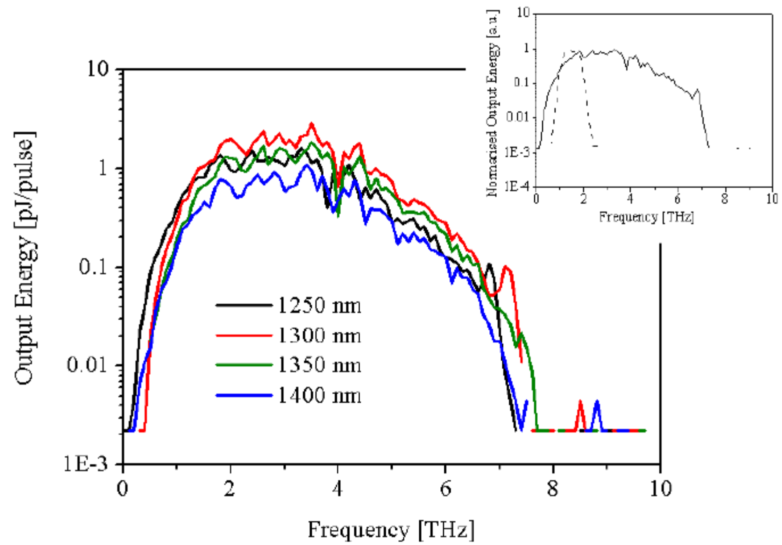
# 1.6 Cherenkov Emitters and Detectors




$$\cos\theta = \frac{V_\omega}{v_{2\omega}} = \frac{n_{\text{pump}}}{n_{\text{THz}}}$$

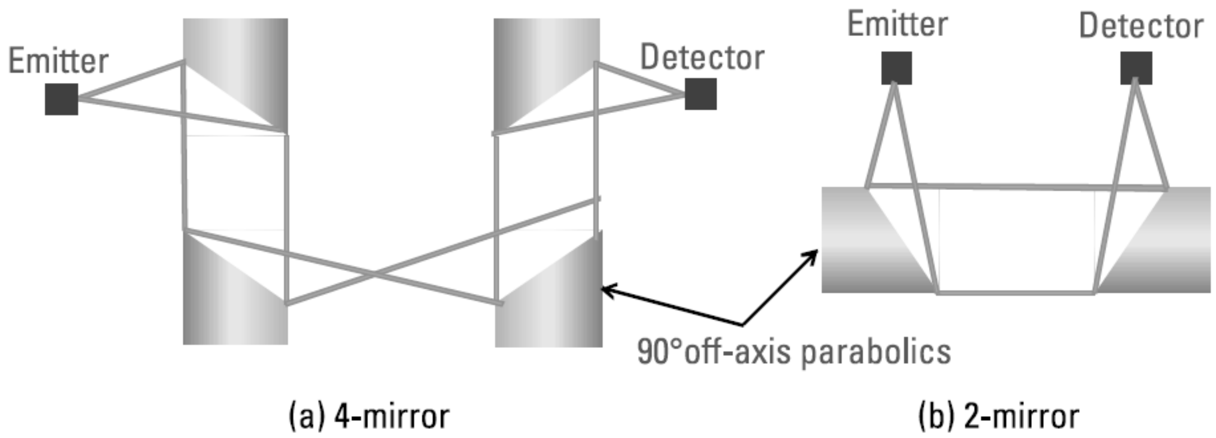



Suizu, K., et al., "Extremely Frequency-Widened Terahertz Wave Generation Using Cherenkov-Type radiation," *Opt. Exp.*, Vol. 17, 2009.
Sutherland, R. L., *Handbook of Nonlinear Optics*, New York: Marcel Dekker, 2003, pp. 91-95.

# Time-Domain Spectrometer Configurations

# 2.1 Transmission

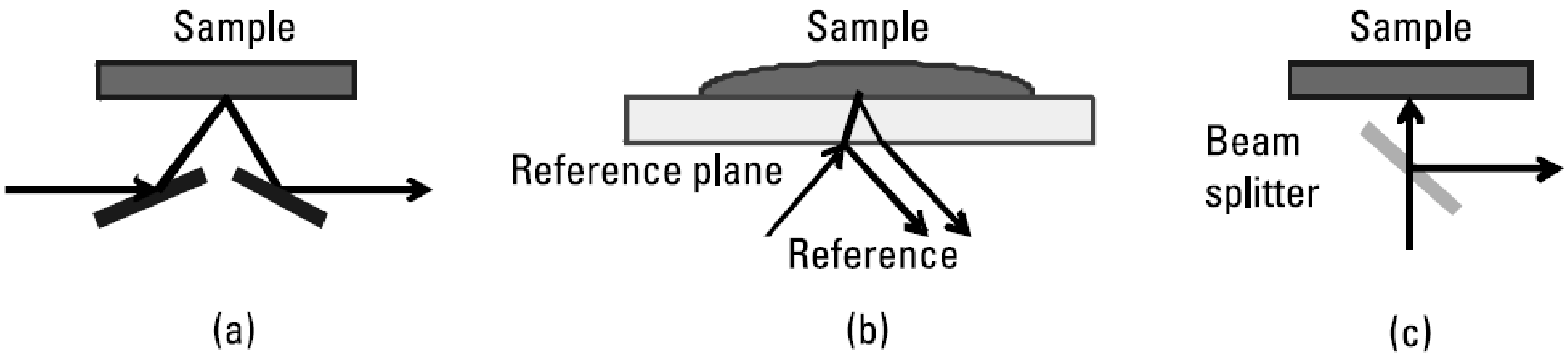



- The great majority of Terhertz TDS system

➔ A more accurate and precise measure of attenuation and phase shift

- Using off-axis parabolic mirrors

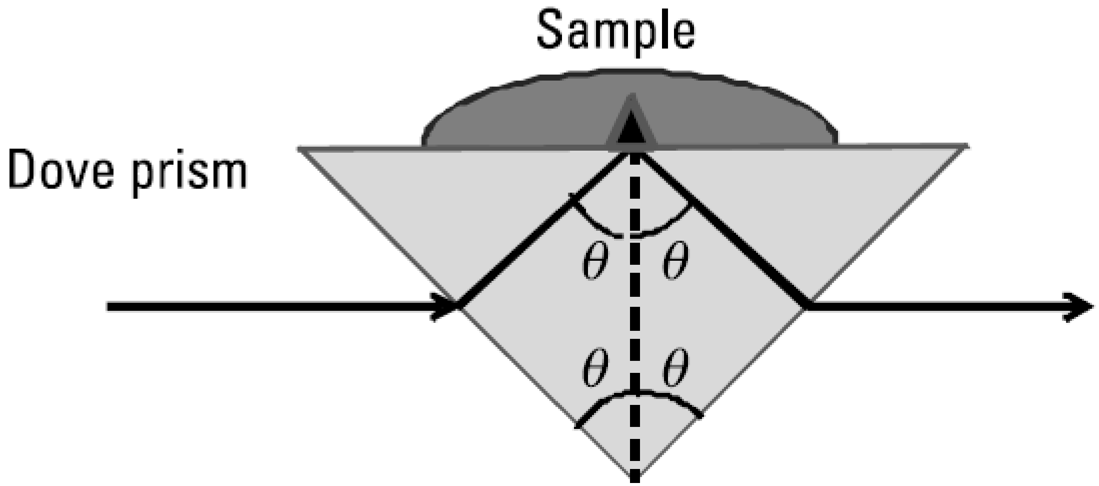
# 2.2 Reflection




- Obaque materials (a)
- Liquid materials (b) ➔ need great care to avoid air gaps
- Normal incidence (c) ➔ the incurred loss of terahertz power is a least 75%

# 2.3 Attenuated Total Reflection

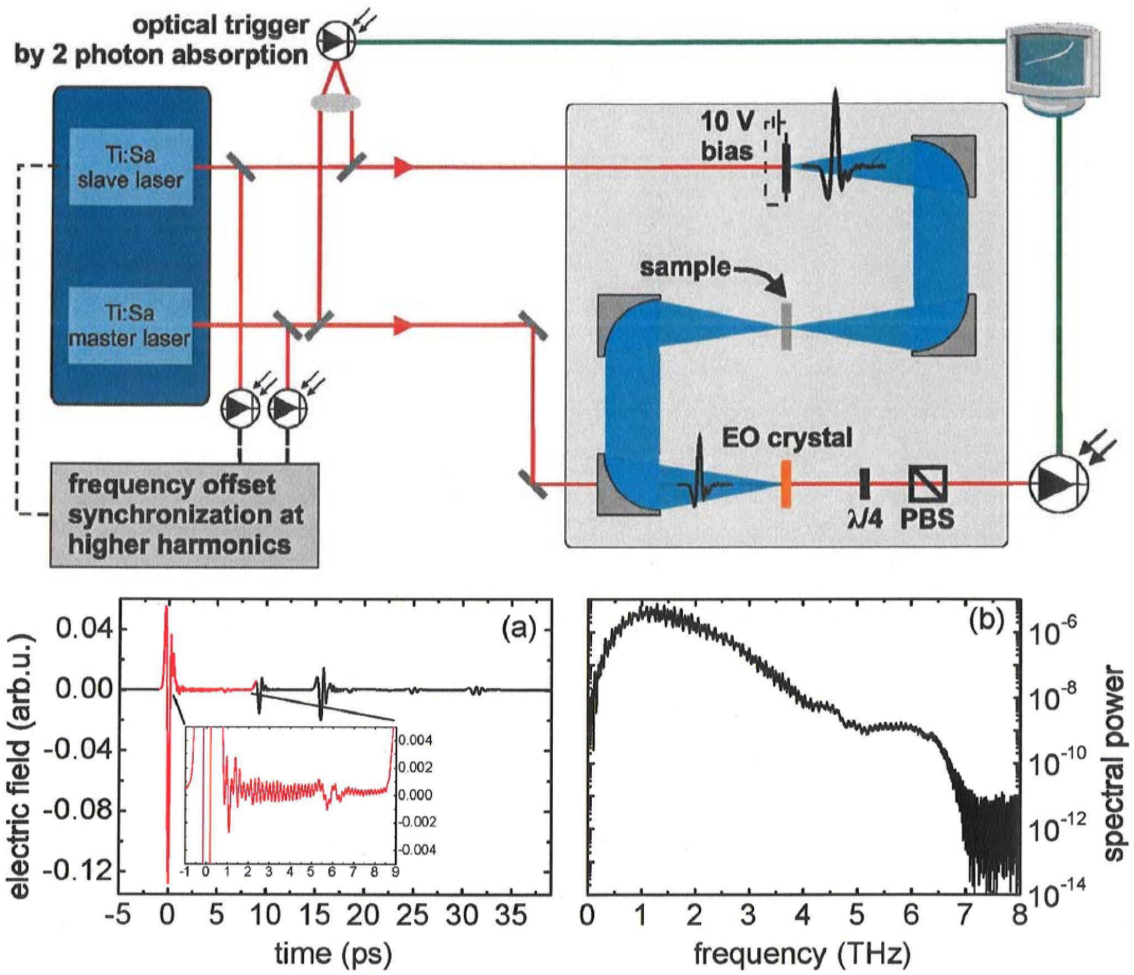
Attenuated Total Reflection (ATR) relies on total internal reflection at an interface, which is modified (attenuated) by the interaction of the evanescent wave with the material of the sample




$$\sin\theta = n_{\text{prism}} \sin\left(2\theta - \frac{\pi}{2}\right)$$

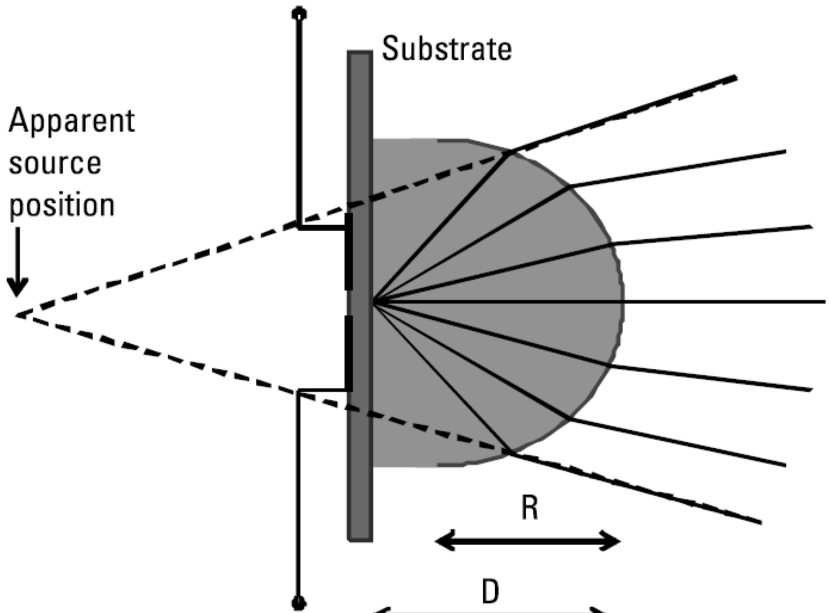
$$d_{\text{evanescent}}(\lambda) = \lambda \frac{n_{\text{prism}}^2 n_{\text{sample}} \cos\theta}{\pi\left(n_{\text{prism}}^2 - n_{\text{sample}}^2\right)\left(n_{\text{prism}}^2 \sin^2\theta - n_{\text{sample}}^2\right)^{1/2}}$$

# 2.4 Asynchronous Optical Sampling




Klatt, G., et al., "High-Resolution Terahertz Spectrometer," IEEE J. Se. Top. Quant. Electron., Vol. 17, 2011.

# 2.5 Substrate Lenses




$$D = R\left(\frac{n+1}{n}\right)$$

# References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