

# Terahertz time-domain spectroscopic ellipsometer calibration and experimental characterization of anisotropic samples

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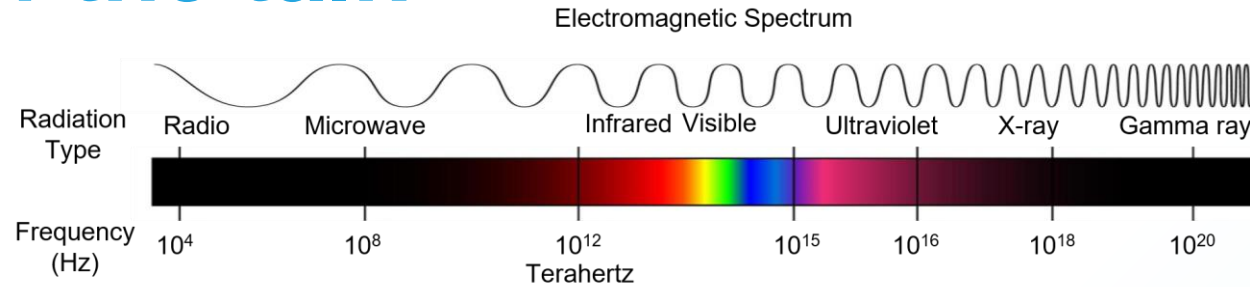
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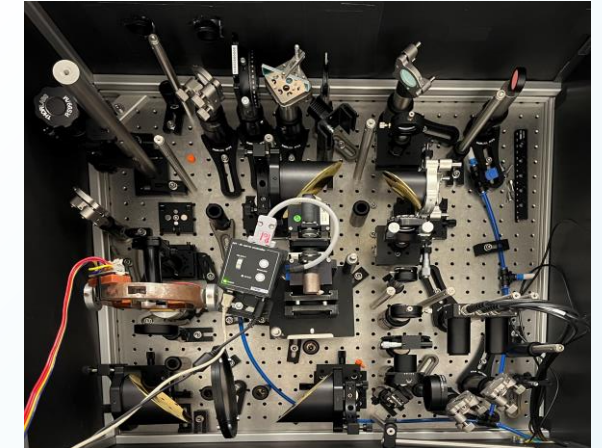
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# Outline of the talk

Motivation



THz time-domain spectroscopic ellipsometry (THz-TDSE)



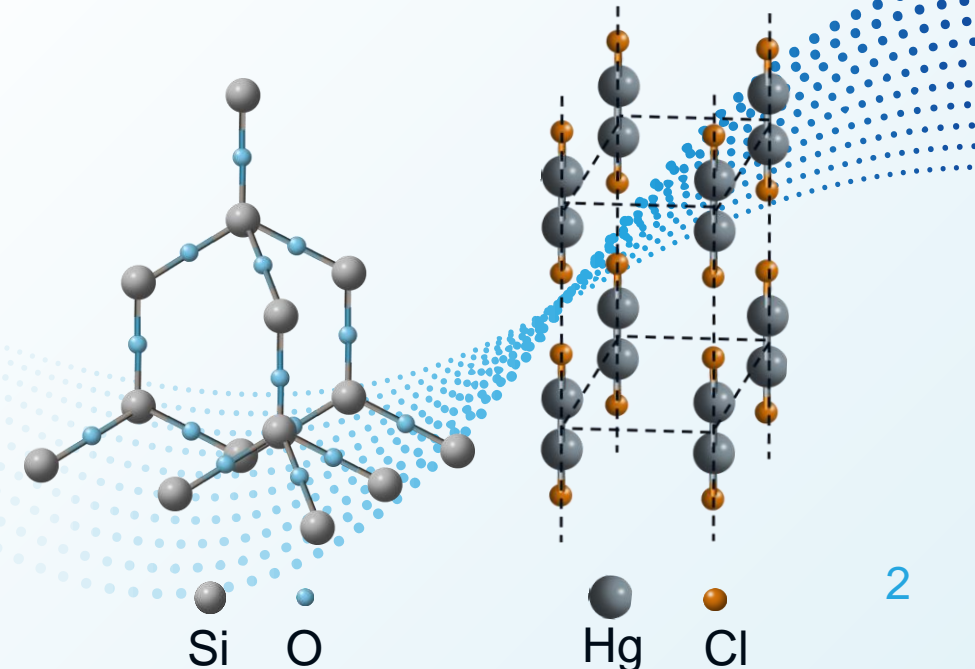
Setup

Eigenvalue calibration

Anisotropic materials measurements

Quartz ( $\text{SiO}_2$ )

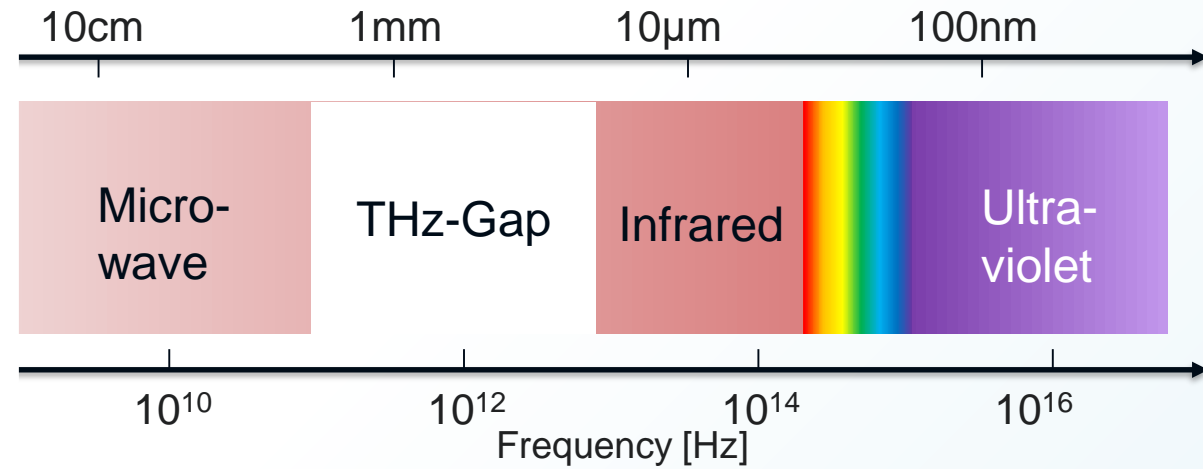
Calomel ( $\text{Hg}_2\text{Cl}_2$ )



# Motivation

## ➤ Terahertz (THz)

- High coherence and very high degree of polarization
- Optical response of large mass molecules
- Complex spectra (phase information)



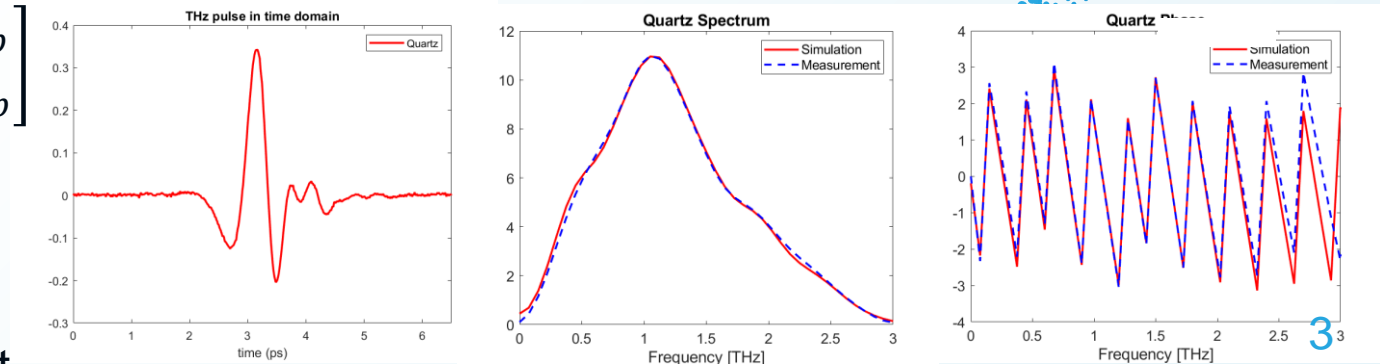
## ➤ THz time domain spectroscopic Ellipsometry

- Complete complex Jones matrix

$$\begin{bmatrix} J_{ss} & J_{sp} \\ J_{ps} & J_{pp} \end{bmatrix}$$

- Absolute phase information

- Ultra-fast dynamic pump-probe measurement



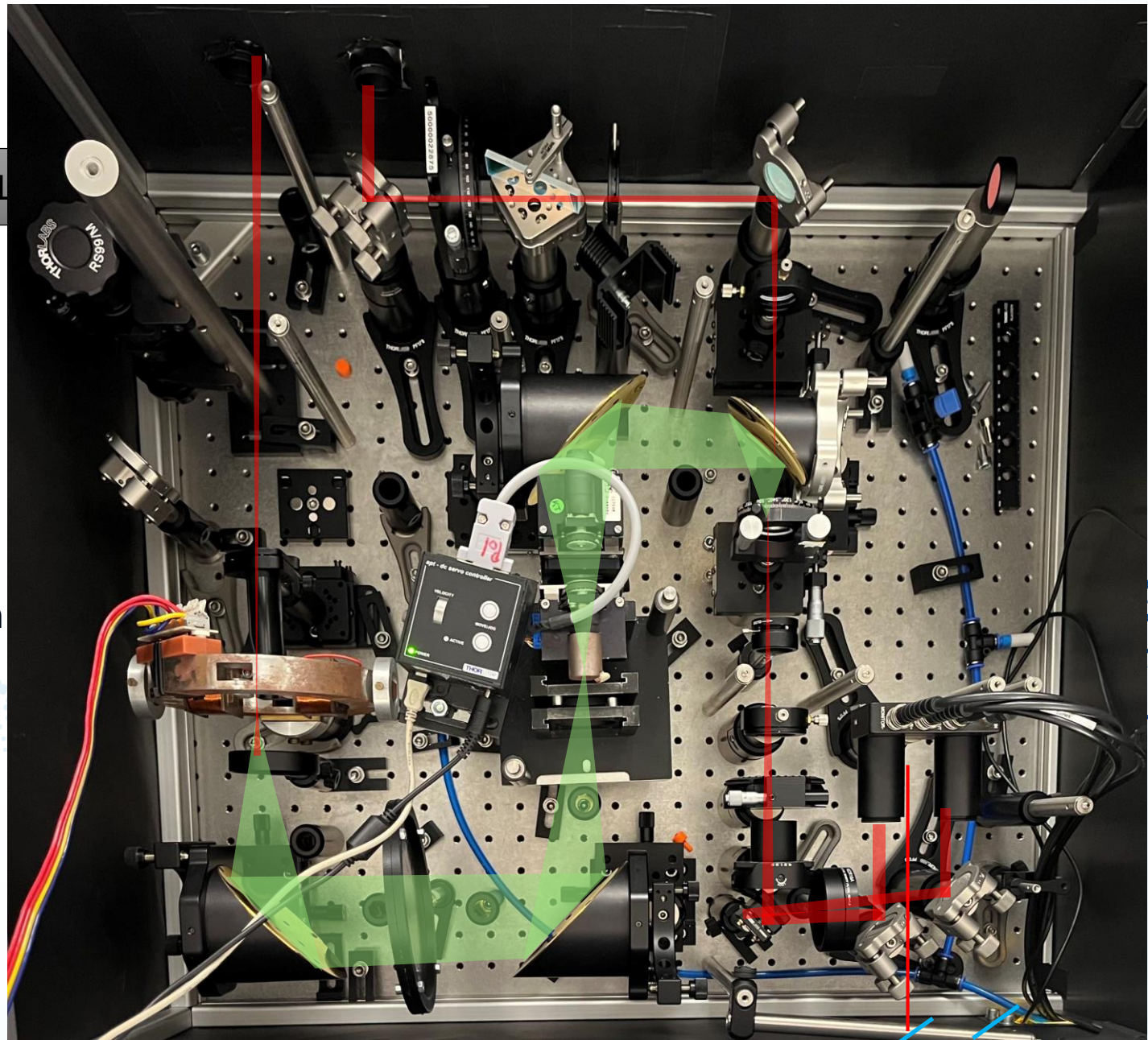
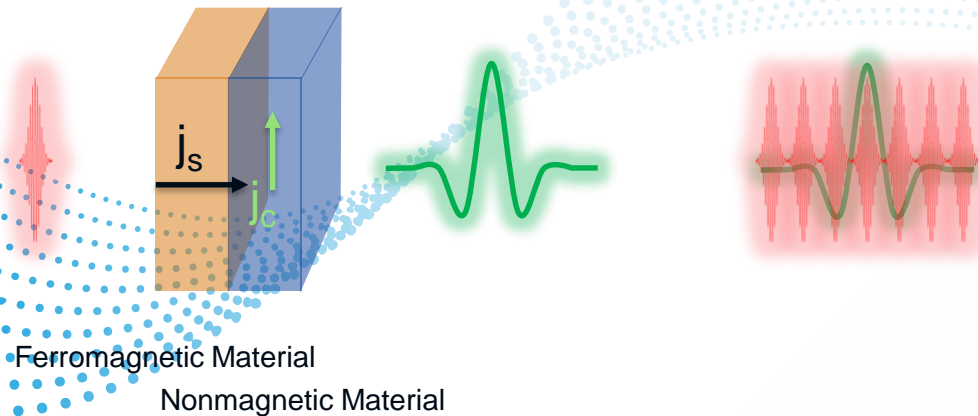


# Sketch of THz-TDSE setup

Laser Source: 808 nm, 75 fs, 5 W laser  
and pulse energy 5 mJ

THz Source: Spintronic THz Emitter (STE):

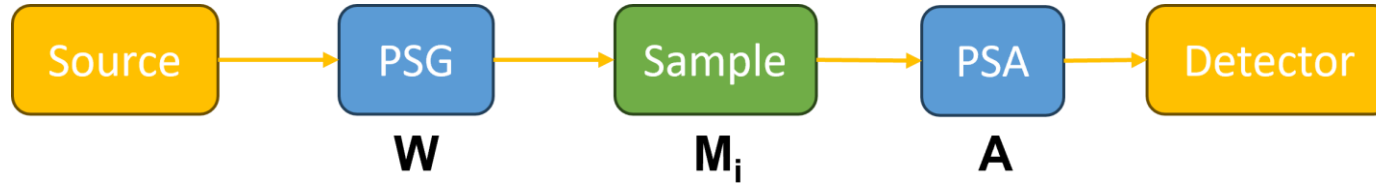
- broad spectrum ( $\sim 20$  THz)
- Linear polarization controlled by magnetization



THz detector: ZnTe crystal with 0.1 mm thickness

# Experimental system description and calibration

Robustness, sensitivity and applicability



- $W$  - Polarization State Generator (PSG)
- $M_i$  - Jones matrix of (calibration) sample
- $A$  - Polarization State Analyzer (PSA)
- $B$  - Detection signal
- $\tilde{w}, \tilde{a}$  - Eigen vector

Unknown:  $A$  and  $W$

Measurement:

$$B_0 = AW$$

$$B_i = AM_i(\alpha_i)W, i \in N$$

Straight through

Samples

Homogeneous Sylvester equations

$$C_i = B_0^{-1} B_i$$

$$C'_i = B_i^{-1} B_0$$

2x2 matrices

Kronecker product

$$H_i(C_i, M_i, I)$$

$$H'_i(C'_i, M_i, I)$$

4x4 matrices

$$K\tilde{w} = 0$$

$$K'\tilde{a} = 0$$

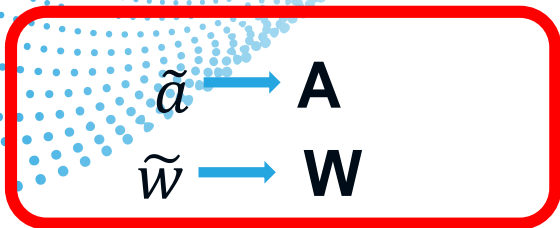
where

$$K = \sum_i H_i^T H_i$$

$$K' = \sum_i H_i'^T H_i'$$

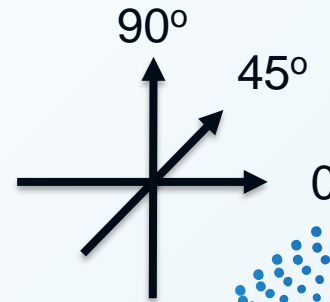
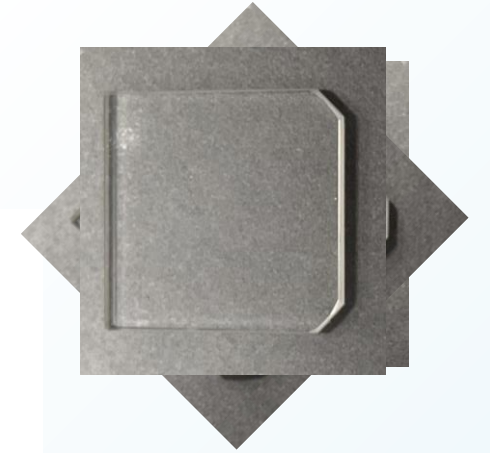
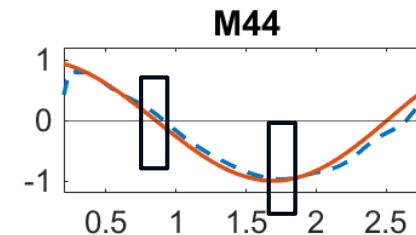
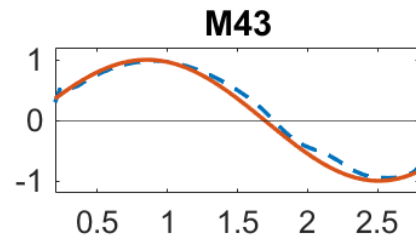
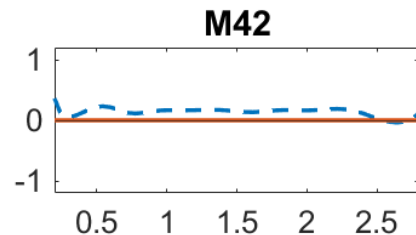
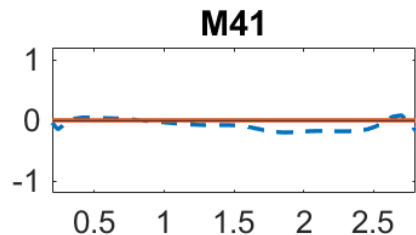
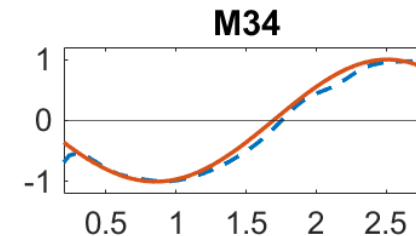
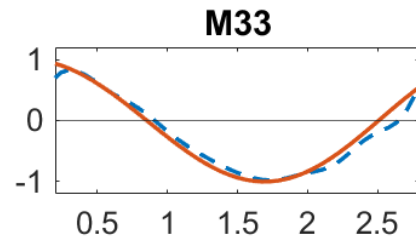
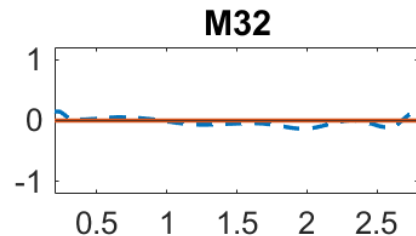
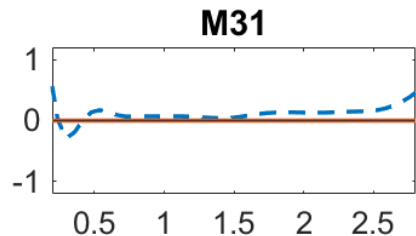
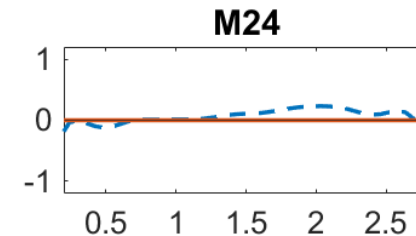
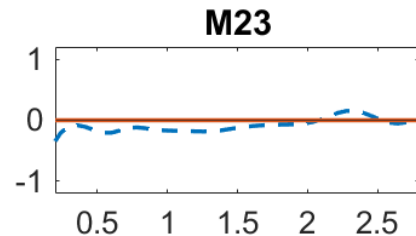
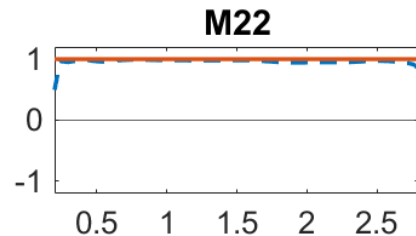
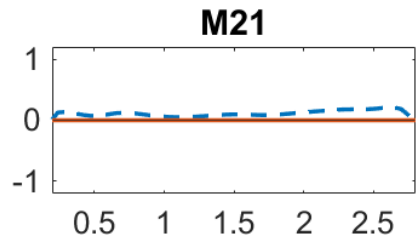
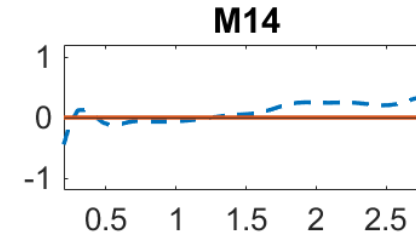
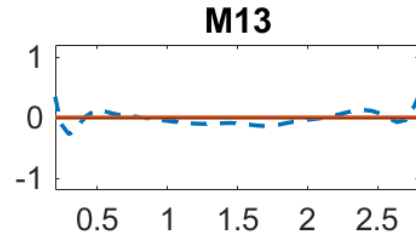
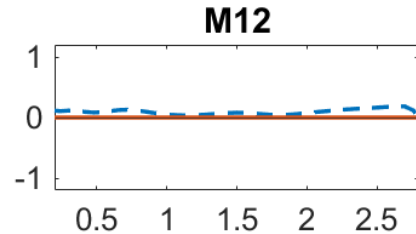
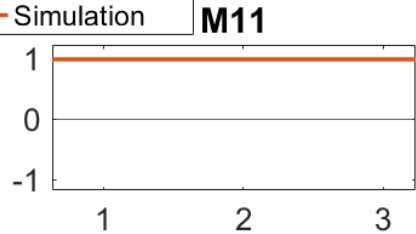
$$M_{\text{unknown}} = A^{-1} B W^{-1} \quad \text{2x2 complex Jones matrix}$$

$$\text{Mueller}_{\text{unknown}} \quad \text{4x4 real value matrix}^5$$



# Quartz measurement with THz TDSE

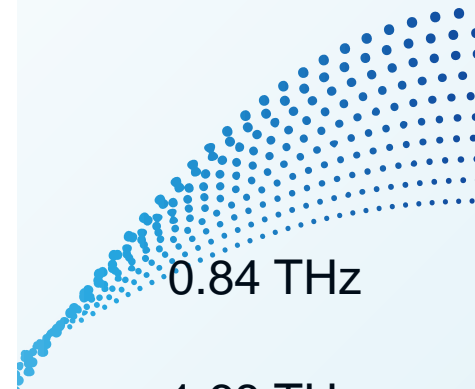
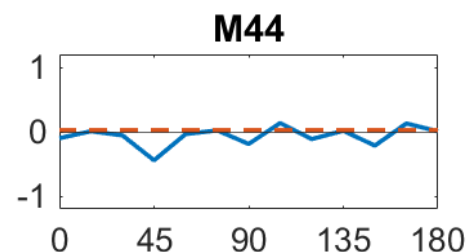
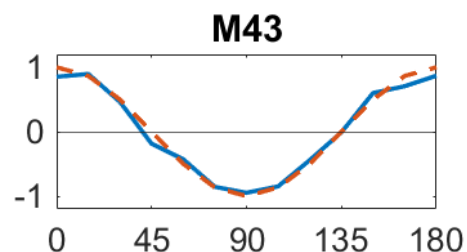
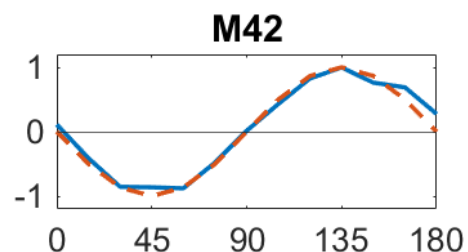
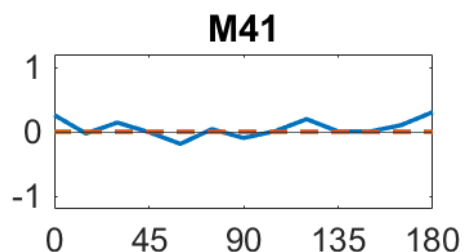
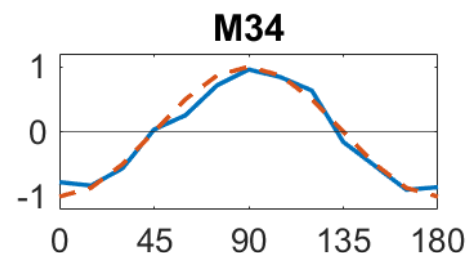
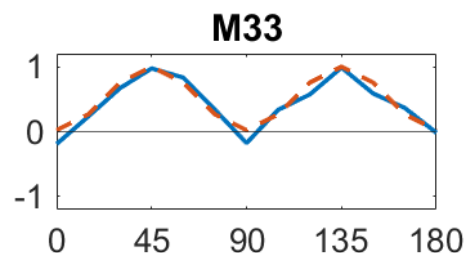
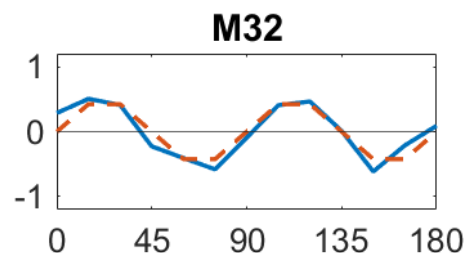
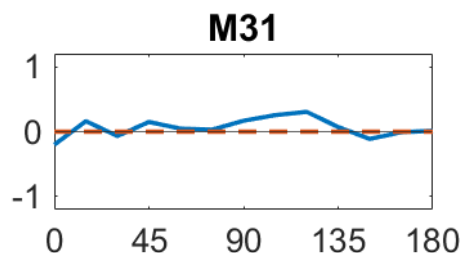
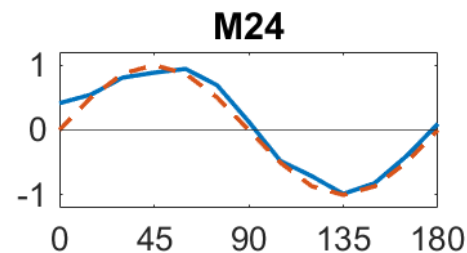
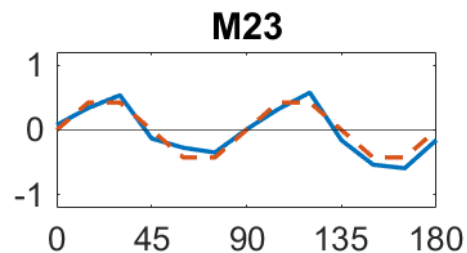
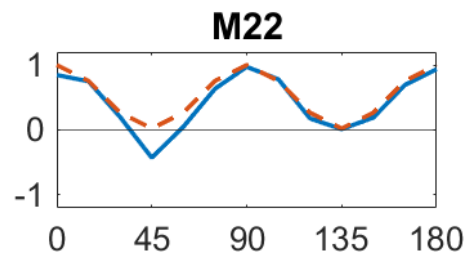
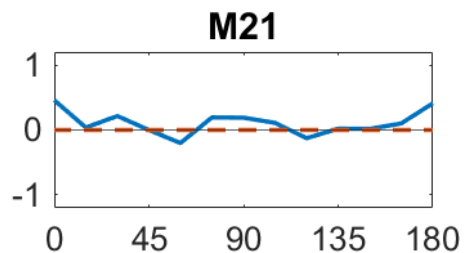
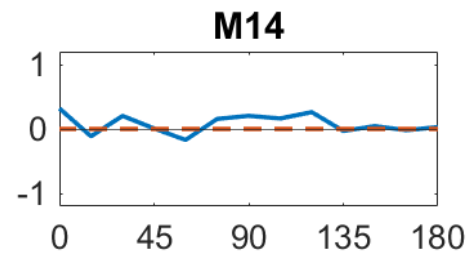
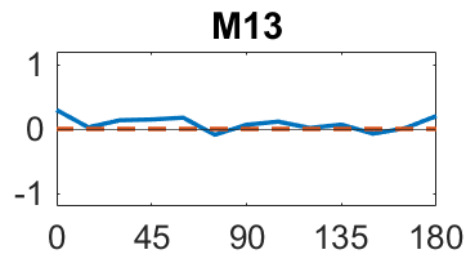
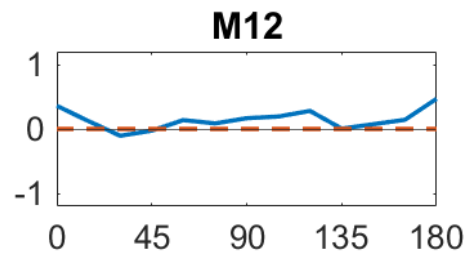
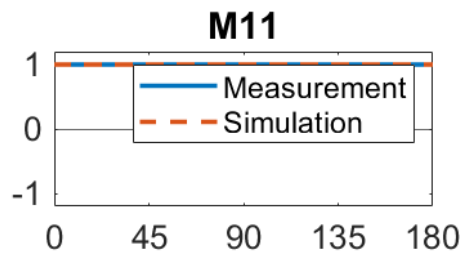
--- Measurement  
— Simulation



1.82 mm thickness



# Mueller matrix of azimuth angles of Quartz



0.84 THz

1.68 THz

2.52 THz

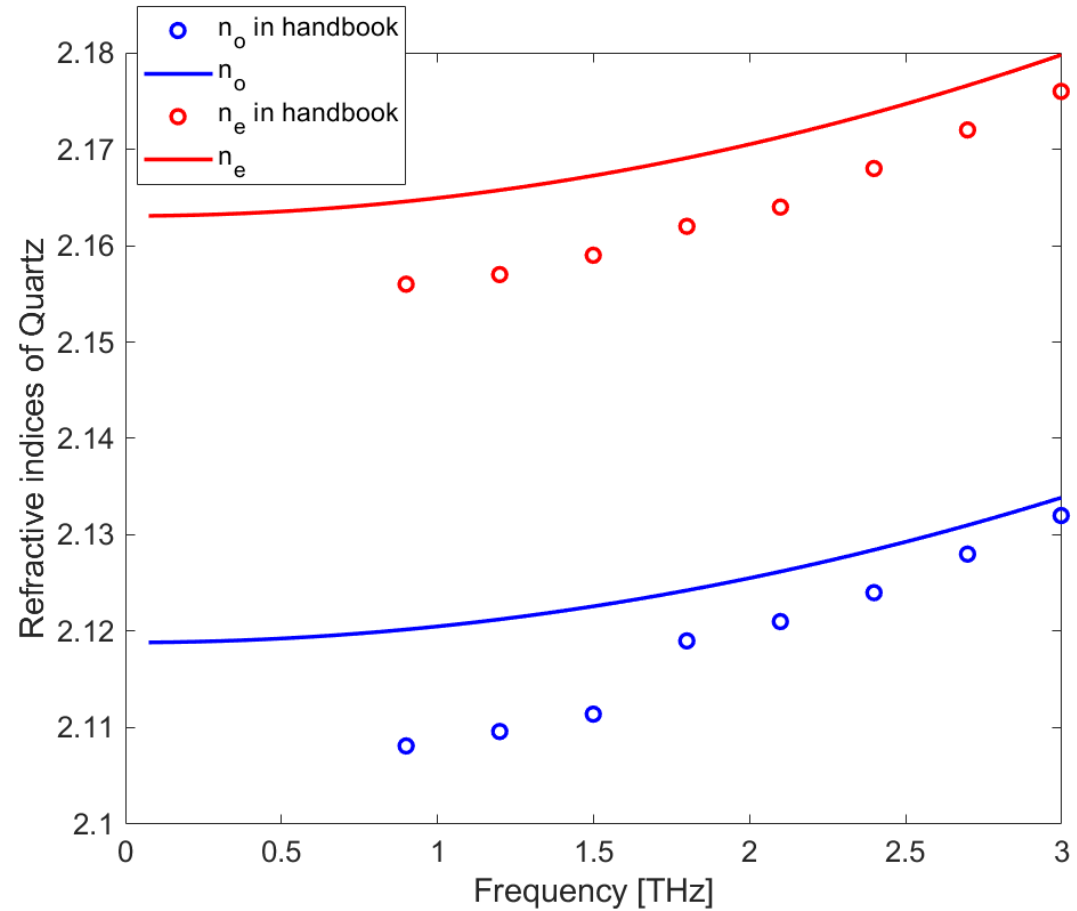
# Fitted optical function of Quartz



$$n_o(\lambda) = n_o + \frac{B_o}{\lambda^2}$$

$$n_e(\lambda) = n_e + \frac{B_e}{\lambda^2}$$

$n_o$	2.119
$B_o$ [m <sup>2</sup> ]	$1.50 \cdot 10^{-10}$
$n_e$	2.167
$B_e$ [m <sup>2</sup> ]	$1.67 \cdot 10^{-10}$

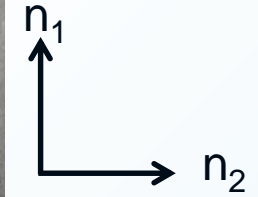


Sample Quartz: Refractive Index

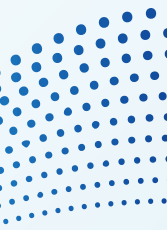
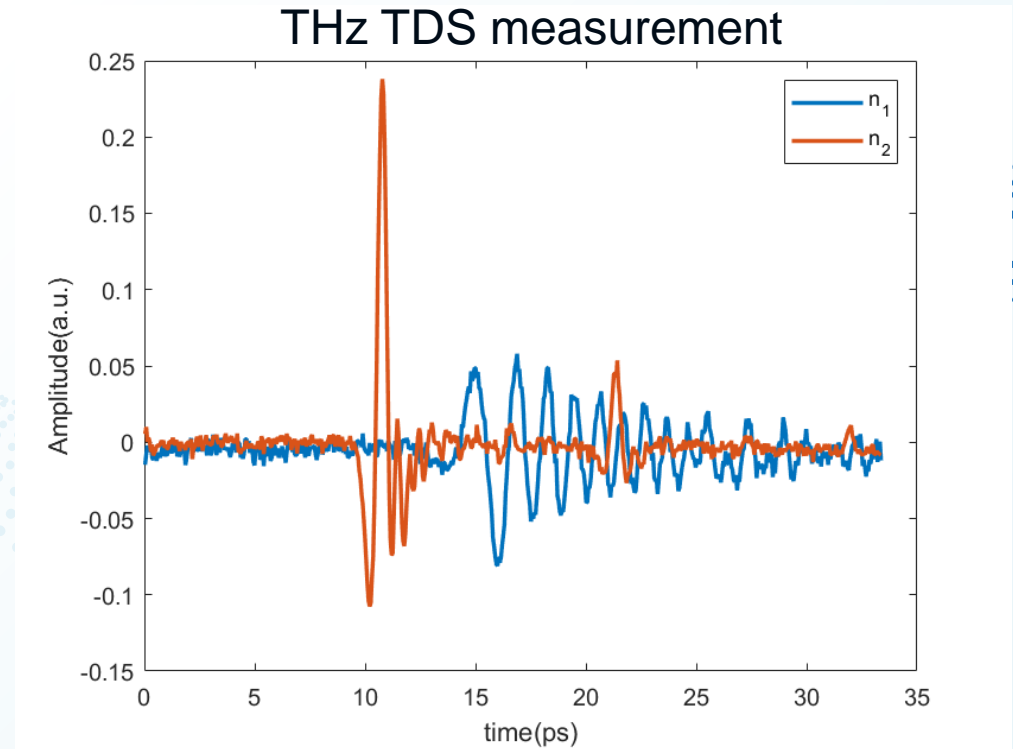
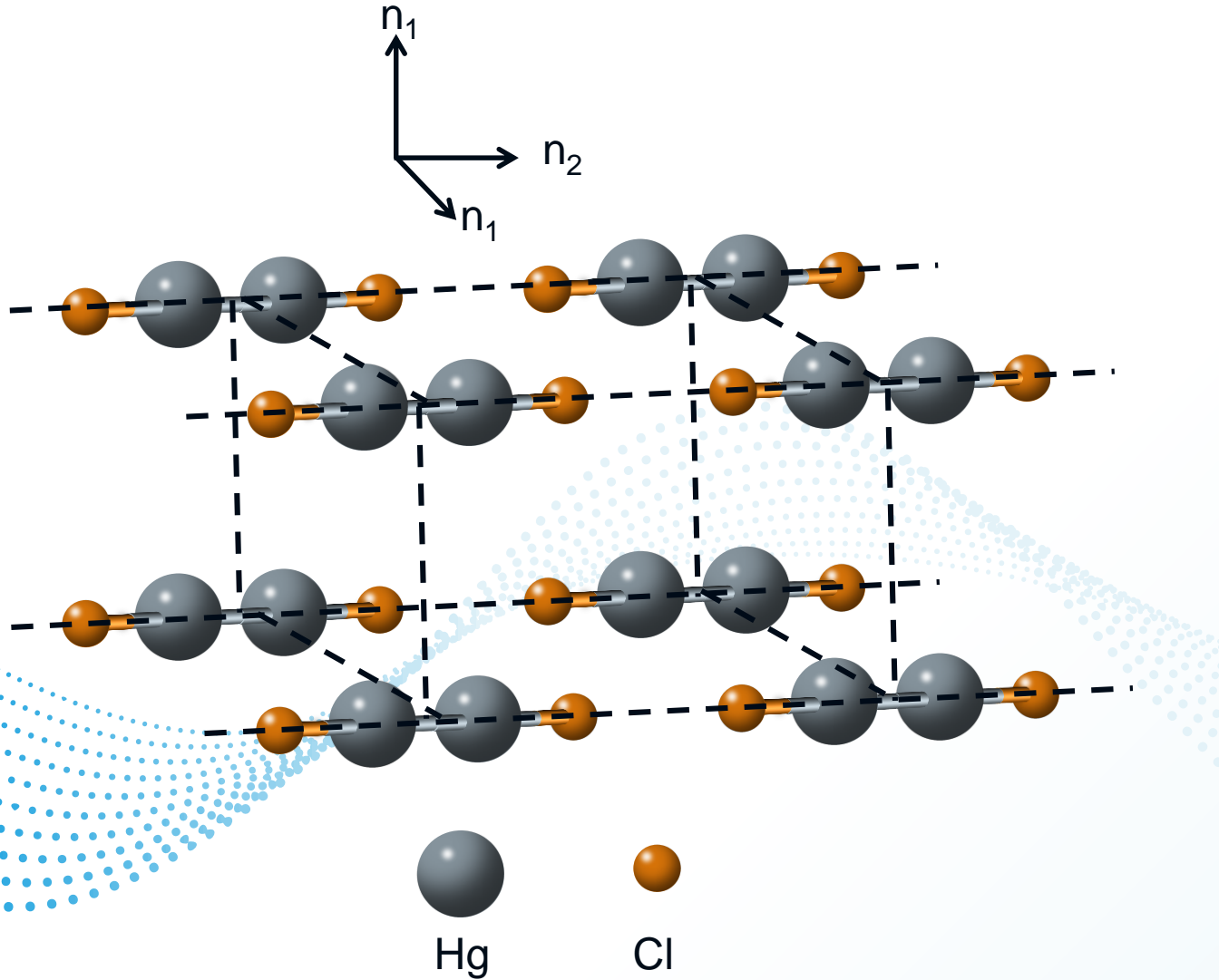


# Measurement Sample: Calomel

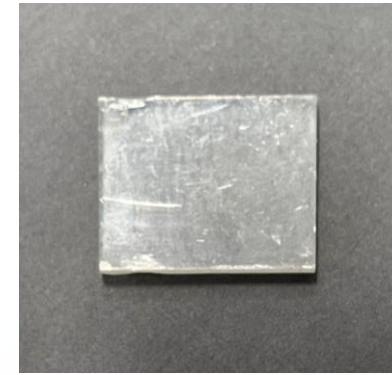
- Broadband spectral range from VIS to THz range
- Strong uniaxial anisotropic property



Calomel 2.15 mm thickness

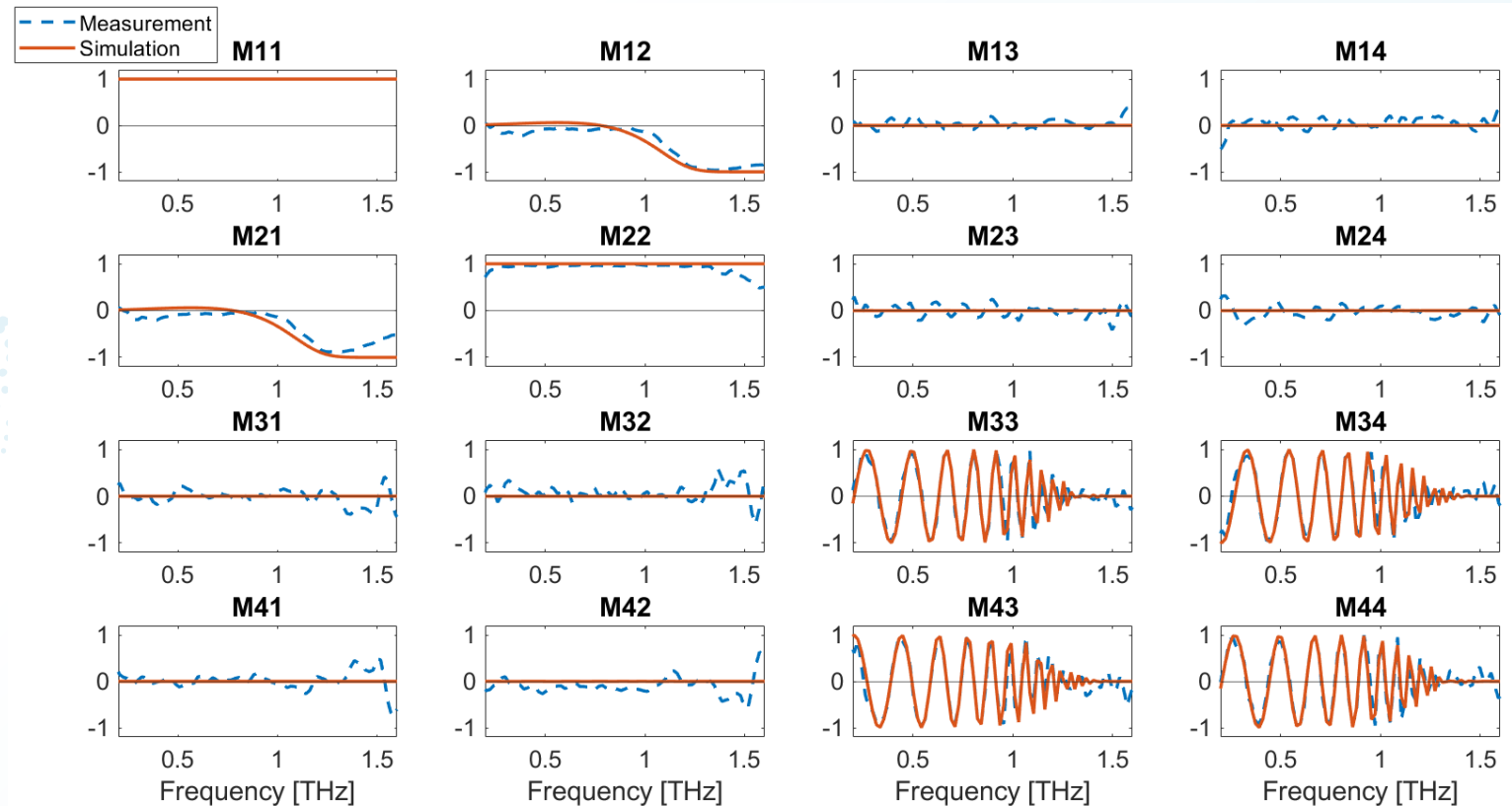


# Calomel measurement with THz TDSE



$$\varepsilon_i = A_i + \frac{B_i^2}{\omega_i^2 - \omega^2 + i\omega\gamma_i}$$

$A_1$	1.29	$A_2$	1.76
$B_1$ [THz]	32.69	$B_2$ [THz]	77.33
$\omega_i$ [THz]	2.00	$\omega_2$ [THz]	6.51
$\gamma_1$	0.68	$\gamma_2$	14.16

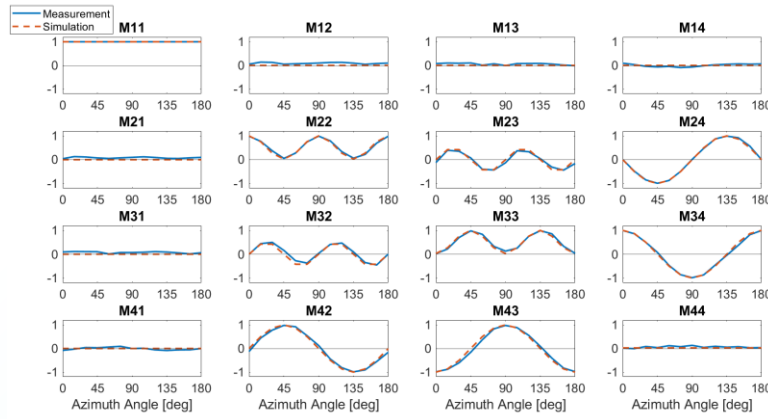
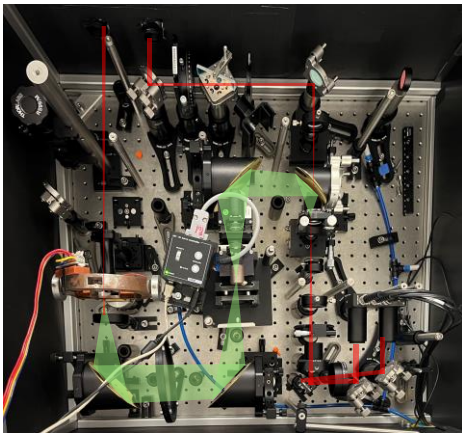


# Conclusion:

THz time domain ellipsometry setup

Eigenvalue Calibration Method

THz ellipsometry measurement: Quartz & Calomel

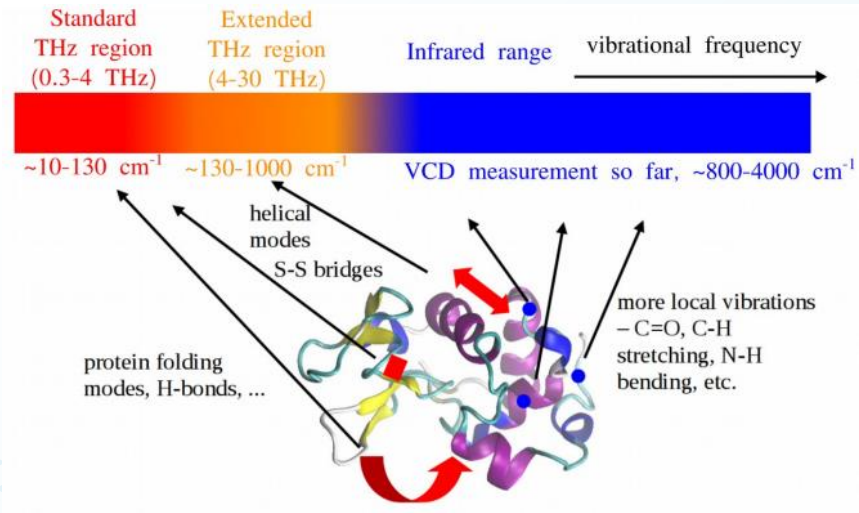


# Application:

THz optical activity

Biomedicine Samples: Amino acids & protein ...

Ultra-fast dynamic pump-probe measurement



# Acknowledgement:

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