High-speed elipsometer

2015/06/11

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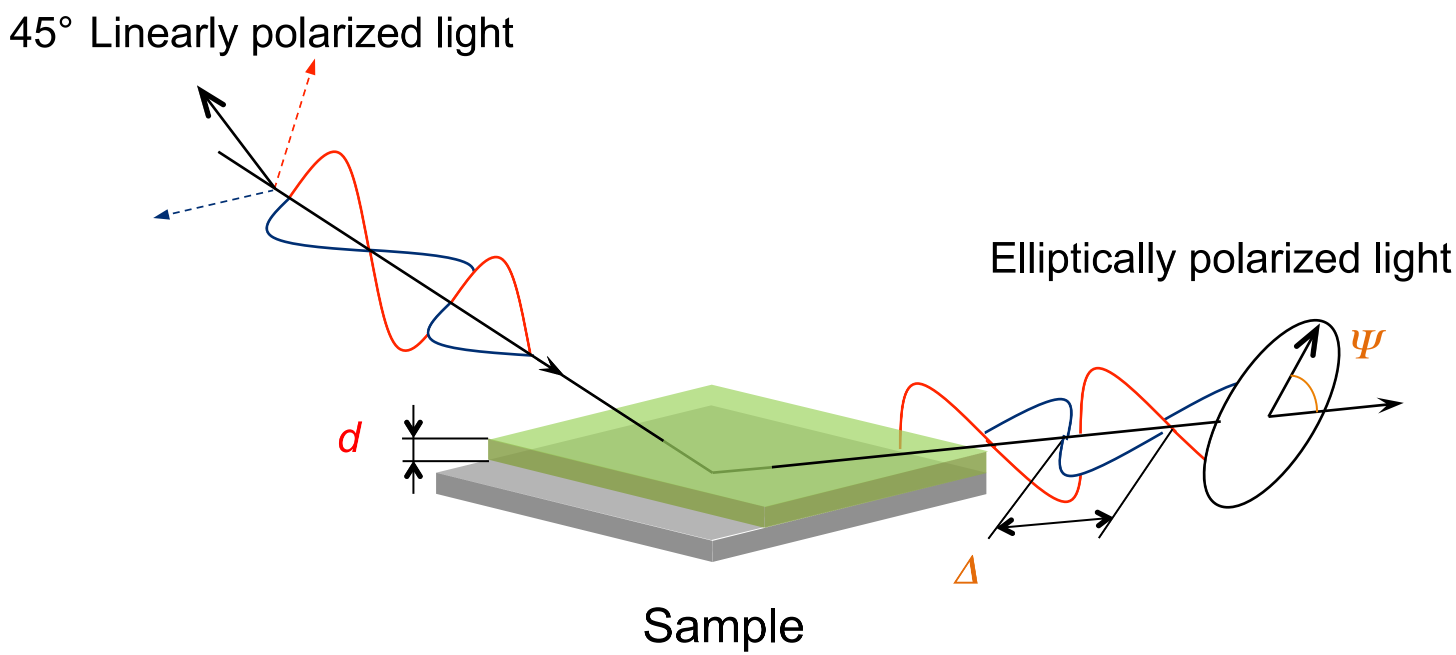
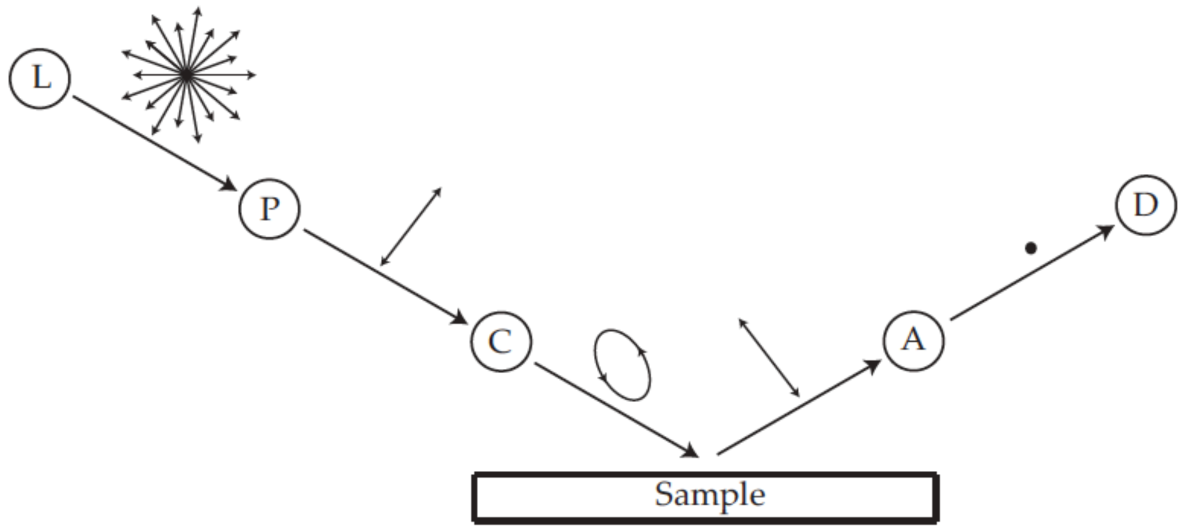
Introduction

- Ellipsometer

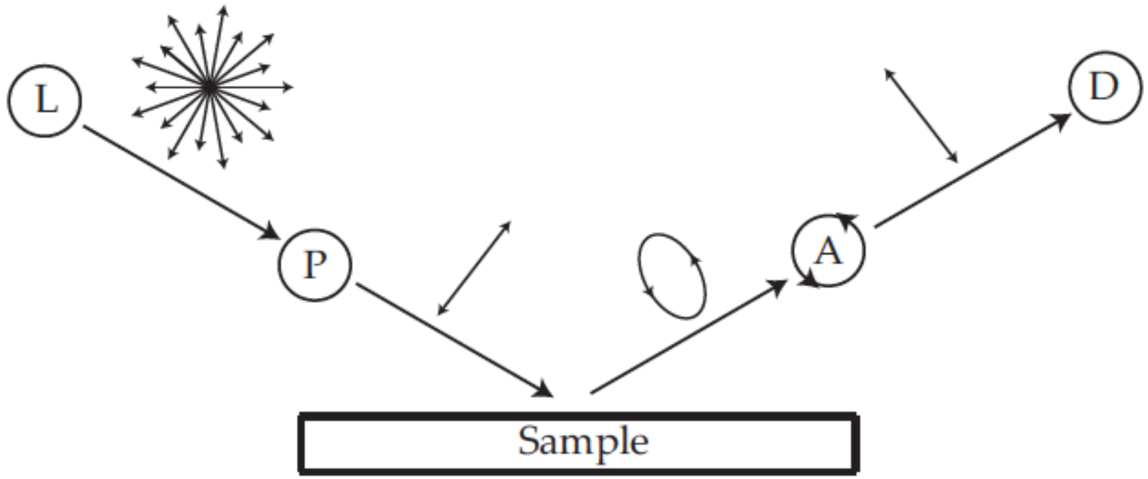


Introduction

- Null ellipsometer



- Photometric ellipsometer



- Determination of retardation parameters of multiple-order wave plate using a phase-sensitive heterodyne ellipsometer

  Ref) C. –H. Hsieh, et. al., Appl. Opt. ***46****: 5944 (2007)*

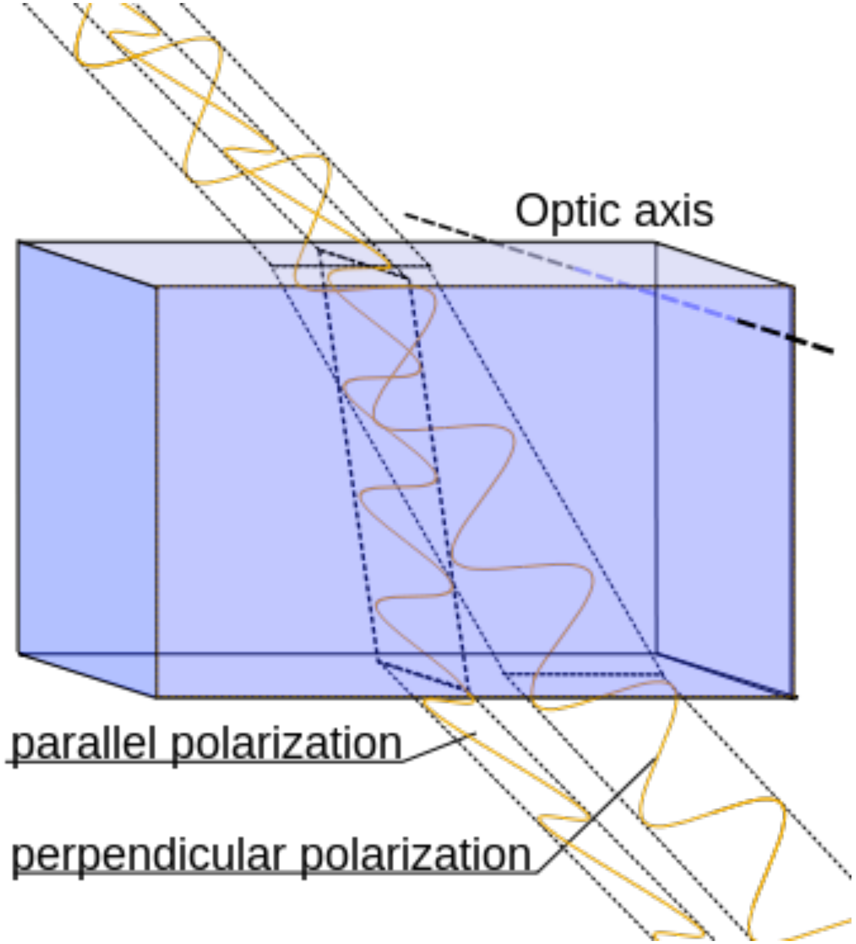
- High speed interferometric ellipsometer

  Ref) C. –C. Tsai, et., al., Opt. Express. ***16****: 7778 (2008)*

- Dual-frequency paired polarization phase shifting ellipsometer

  Ref) C. –J. Yu., et., al., Opt. commun. ***282****:1516 (2009)*

Birefringent material



$$\Delta n = n_e - n_o$$

Experimental setup

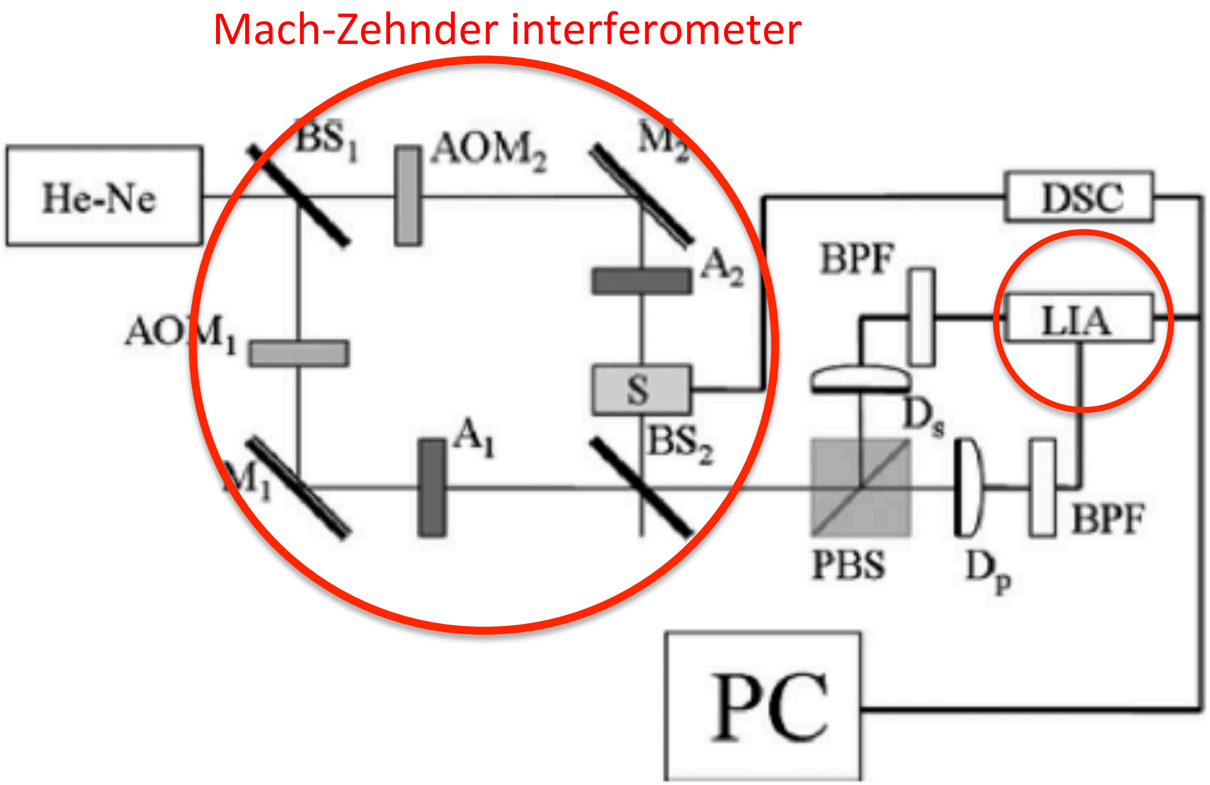
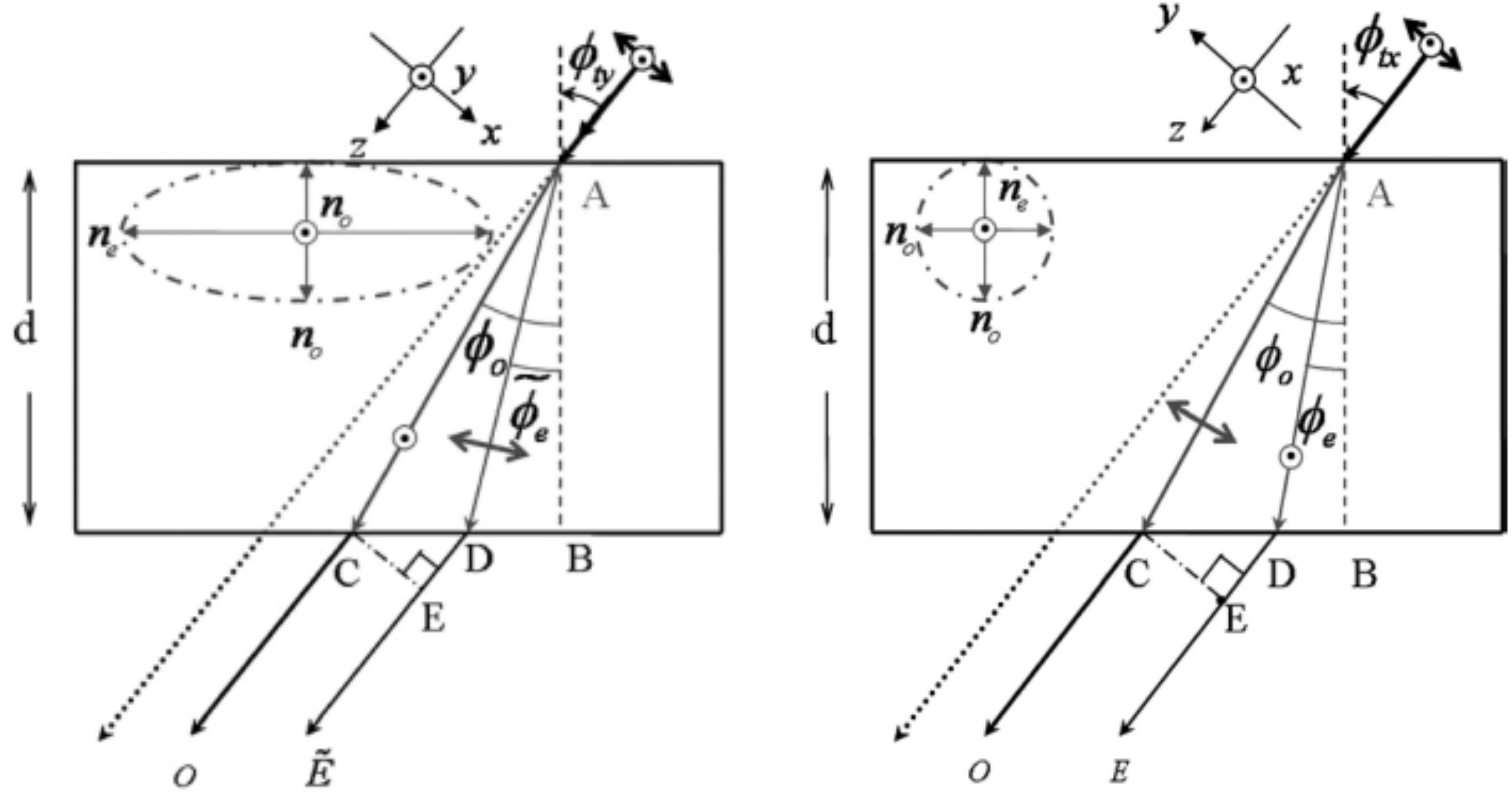


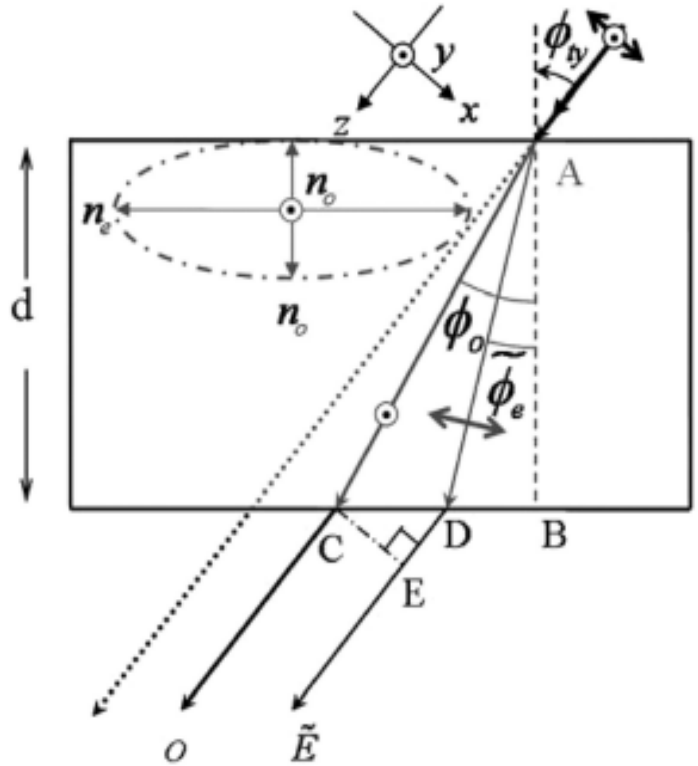
Fig. 1. Experimental setup: **BS$_1$**, **BS$_2$**: beam splitters, **AOM$_1$**, **AOM$_2$**: acousto-optic modulators, **M$_1$**, **M$_2$**: mirrors, **A$_1$**, **A$_2$**: analyzers, **S**: test sample on rotation stage, **PBS**: polarization beam splitter, **D$_p$**, **D$_s$**: photo detectors, **BPF**: band-pass filter, **LIA**: lock-in amplifier, **DSC**: digital stepping controller, **PC**: personal computer.

Method

- Multiple-order wave plate
  - A linear birefringent material



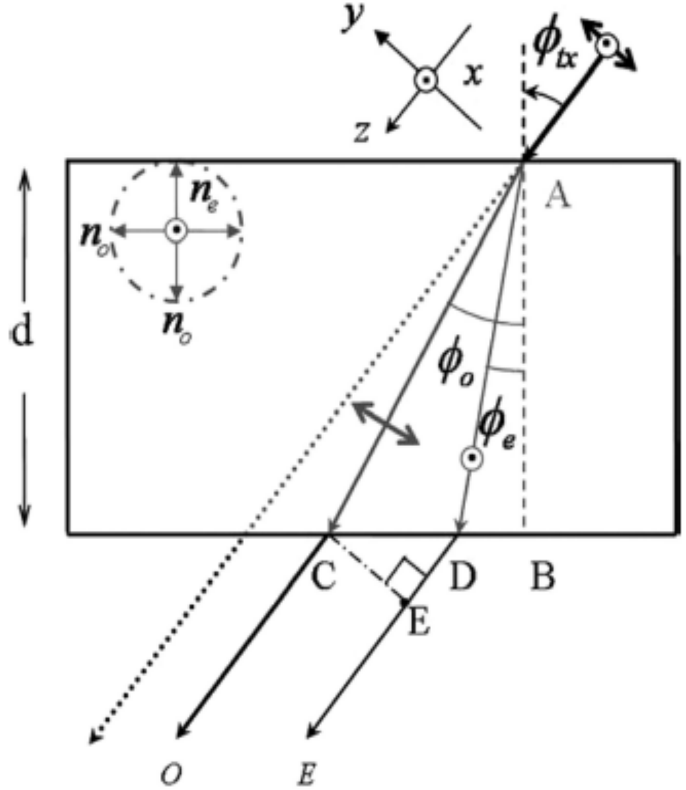
Method



$$\begin{aligned}\delta_{ty} &= \delta_s - \delta_p \\ &= \frac{2\pi}{\lambda}(n_o\overline{AC}) - \frac{2\pi}{\lambda}(\tilde{n}_e\overline{AD} + \overline{DE}) \\ &= \frac{2\pi}{\lambda} d\left(n_o \cos\phi_o - \tilde{n}_e \cos\tilde{\phi}_e\right) \\ &= \frac{2\pi}{\lambda} d\left(\sqrt{n_o{}^2 - \sin^2\phi_{ty}} - \sqrt{n_e{}^2 - \frac{n_e{}^2}{n_o{}^2}\sin^2\phi_{ty}}\right),\end{aligned}$$

$$\delta_{ty} - \delta_0 = \frac{2\pi}{\lambda} d\left[\left(\sqrt{n_o{}^2 - \sin^2\phi_{ty}} - \sqrt{n_e{}^2 - \frac{n_e{}^2}{n_o{}^2}\sin^2\phi_{ty}}\right) - (n_o - n_e)\right], \quad (10)$$

Method

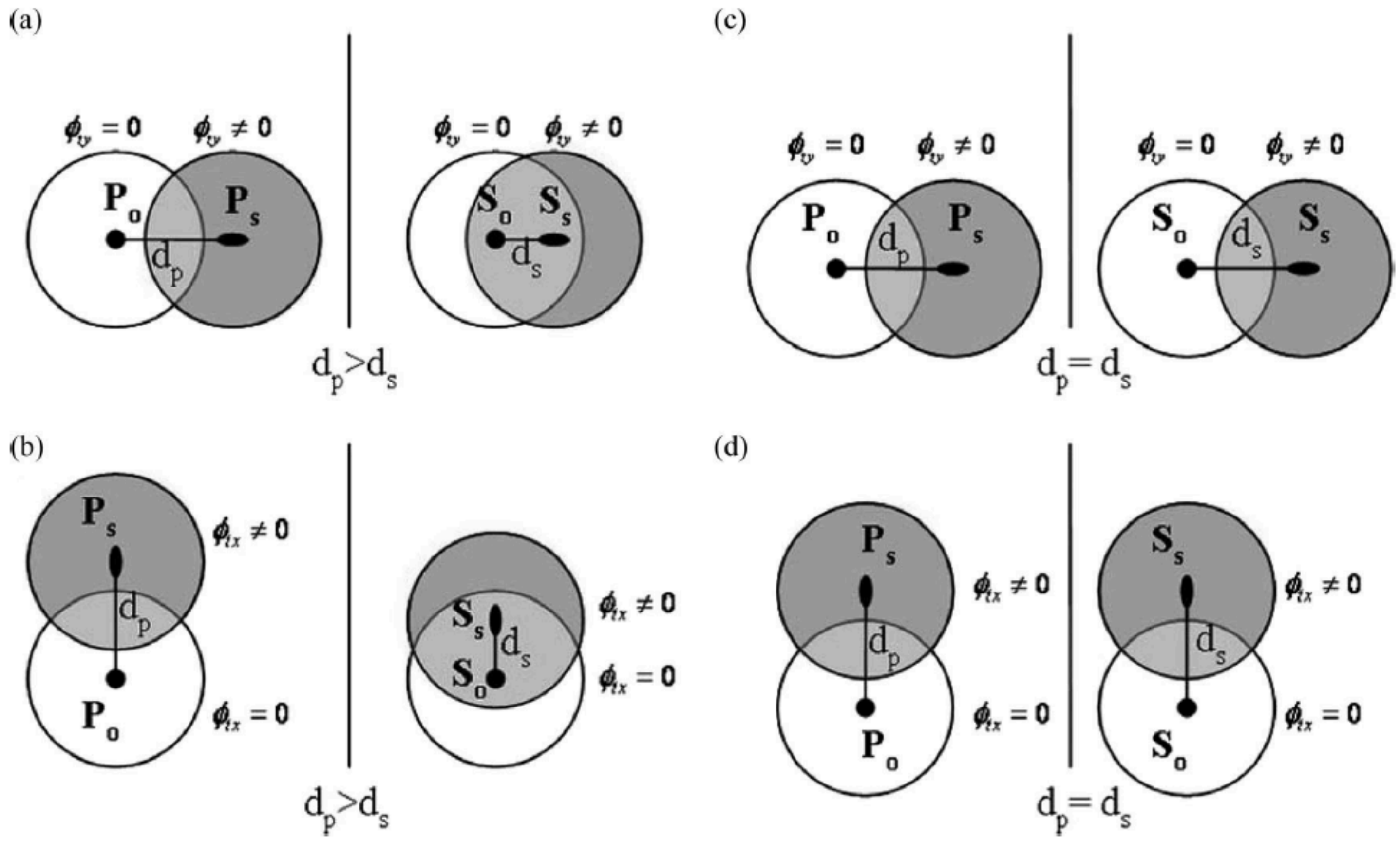


$$\delta_{tx} - \delta_0 = \frac{2\pi}{\lambda} d\Big[\Big(\sqrt{n_o{}^2 - \sin^2\phi_{tx}} - \sqrt{n_e{}^2 - \sin^2\phi_{tx}}\Big) - (n_o - n_e)\Big], \quad (11)$$

For a linearly birefringent medium：

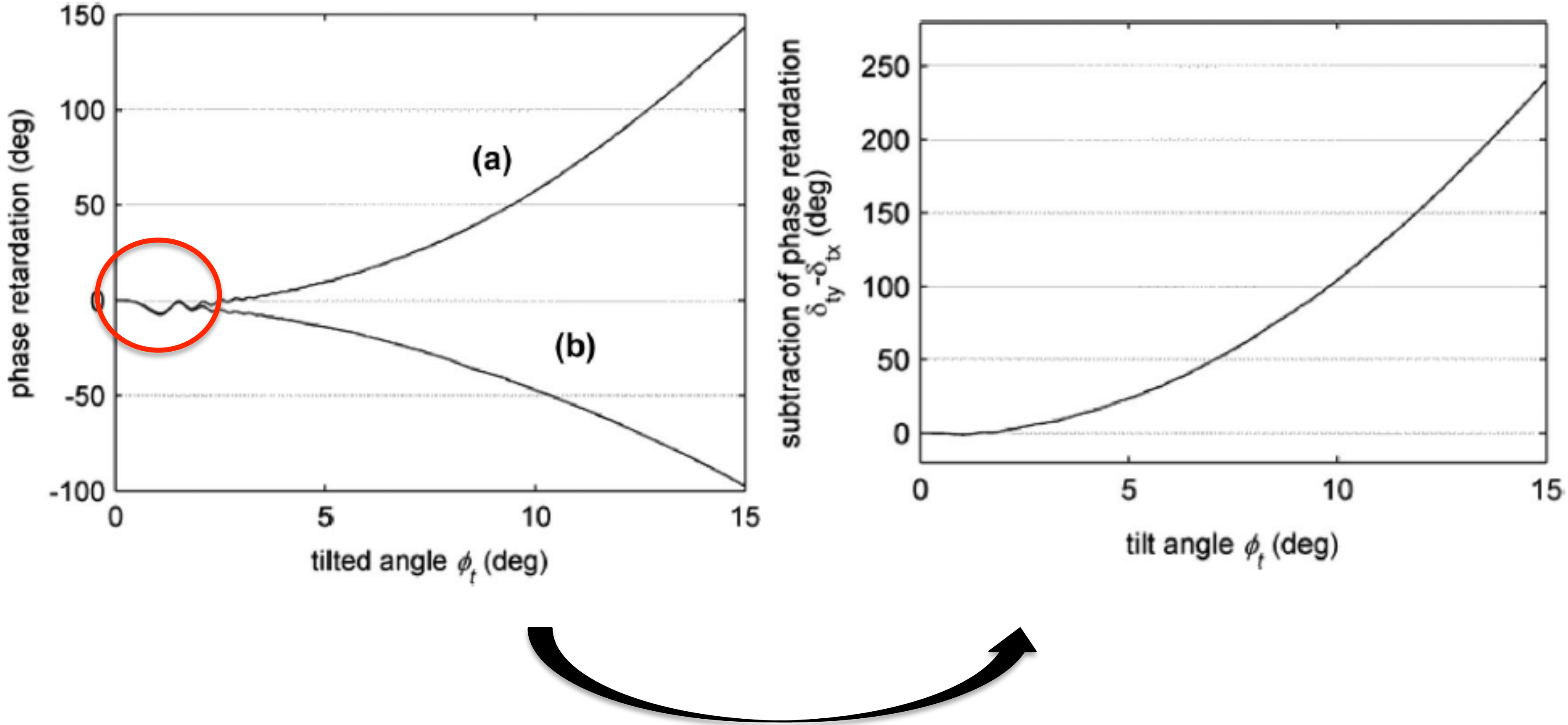
$$\frac{2\pi}{\lambda} d(n_e - n_o) = 2m\pi + \Gamma.$$

Method

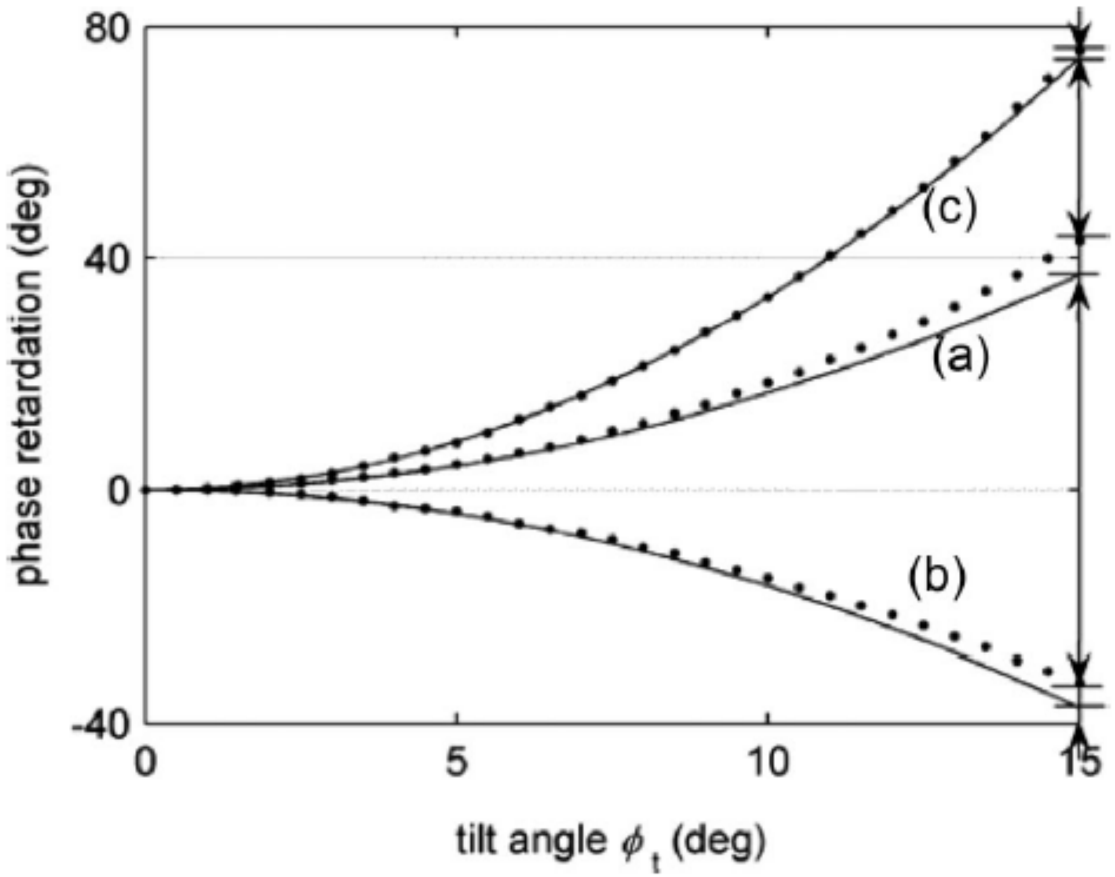


$$(\delta_{ty} - \delta_{tx})/(2m\pi + \Gamma) = \left(\sqrt{n_e^2 - \sin^2 \phi_t} - \sqrt{n_e^2 - n_e^2 \sin^2 \phi_t / n_o^2}\right) \Big/ (n_e - n_o).$$

Results


150
100
50
0
-50
-100
0
5
10
15
phase retardation (deg)
tilted angle ϕ_t (deg)
(a)
(b)
subtraction of phase retardation
$\delta_{ty}-\delta_{tx}$ (deg)
250
200
150
100
50
0
0
5
10
15
tilt angle ϕ_t (deg)

Results



- m=7
- n_0=1.5427
- n_e=1.5518
- Error: 0.05%

Summary

- highly sensitive and accurate measurement of retardation parameters (RPs), which includes the refractive indices of the extraordinary ray n_e and ordinary ray n_o, is obtained by this method.

- Determination of retardation parameters of multiple-order wave plate using a phase-sensitive heterodyne ellipsometer

  *Ref) C. –H. Hsieh, et. al., Appl. Opt. **46**: 5944 (2007)*

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Method

- The polarized heterodyne signals at photo-detectors D_P and D_S can be expressed by

$$I_P(\delta\omega t) = A_{P1}^{2} + A_{P2}^{2} + 2A_{P1}A_{P2}\cos[\delta\omega t + \delta\phi_P],$$

$$I_S(\delta\omega t) = A_{S1}^{2} + A_{S2}^{2} + 2A_{S1}A_{S2}\cos[\delta\omega t + \delta\phi_S],$$

- set $\alpha = \delta\omega t + \frac{\delta\phi_S + \delta\phi_P}{2}$, $\beta = \frac{\delta\phi_S - \delta\phi_P}{2}$, $\kappa_P = 2A_{P1}A_{P2}$, and $\kappa_S = 2A_{S1}A_{S2}$

$$\Rightarrow \quad I_P(\delta\omega t) \equiv \kappa_P \cos[\alpha - \beta],$$

$$I_S(\delta\omega t) \equiv \kappa_S \cos[\alpha + \beta],$$

Method

- The output signal, from DA

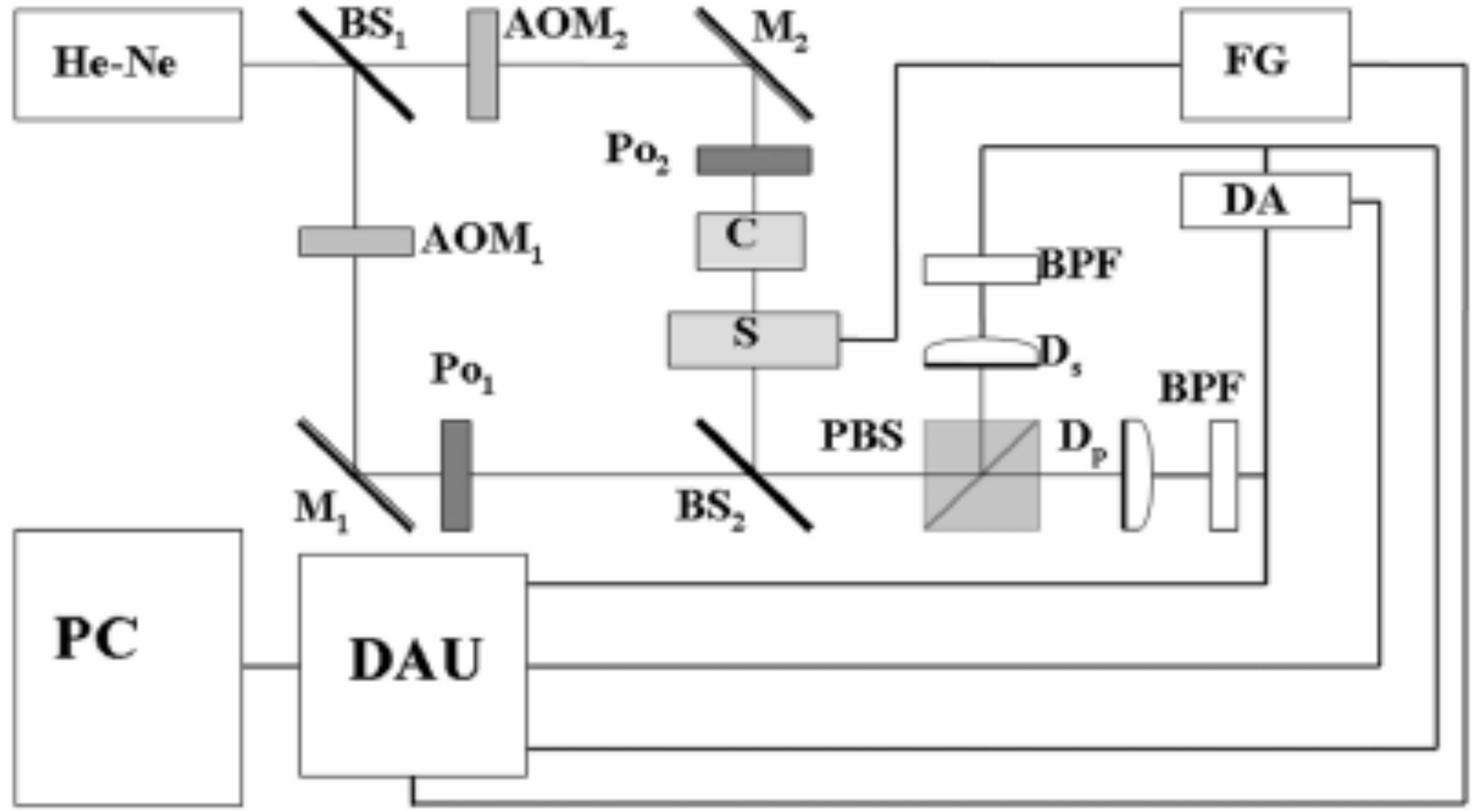
$$
\begin{aligned}
I_{Diff}(\delta\omega t) &= I_S(\delta\omega t) - I_P(\delta\omega t) \\
&= (\kappa_S - \kappa_P)\cos\beta\cos\alpha - (\kappa_S + \kappa_P)\sin\beta\sin\alpha \\
&= \cos\gamma\cos\alpha - \sin\gamma\sin\alpha = \sqrt{\kappa_S{}^2 + \kappa_P{}^2 - 2\kappa_S\kappa_P\cos(\delta\phi_S - \delta\phi_P)}\cos(\alpha+\gamma) \\
&= \kappa_{Diff}\cos(\alpha+\gamma)
\end{aligned}
$$

$$\kappa_{Diff} = \sqrt{\kappa_S{}^2 + \kappa_P{}^2 - 2\kappa_S\kappa_P\cos(\boxed{\delta\phi_S - \delta\phi_P})}$$

$$\Rightarrow \quad \Delta = \cos^{-1}\left[\frac{\kappa_P{}^2 + \kappa_S{}^2 - \kappa_{Diff}{}^2}{2\kappa_P\kappa_S}\right],$$

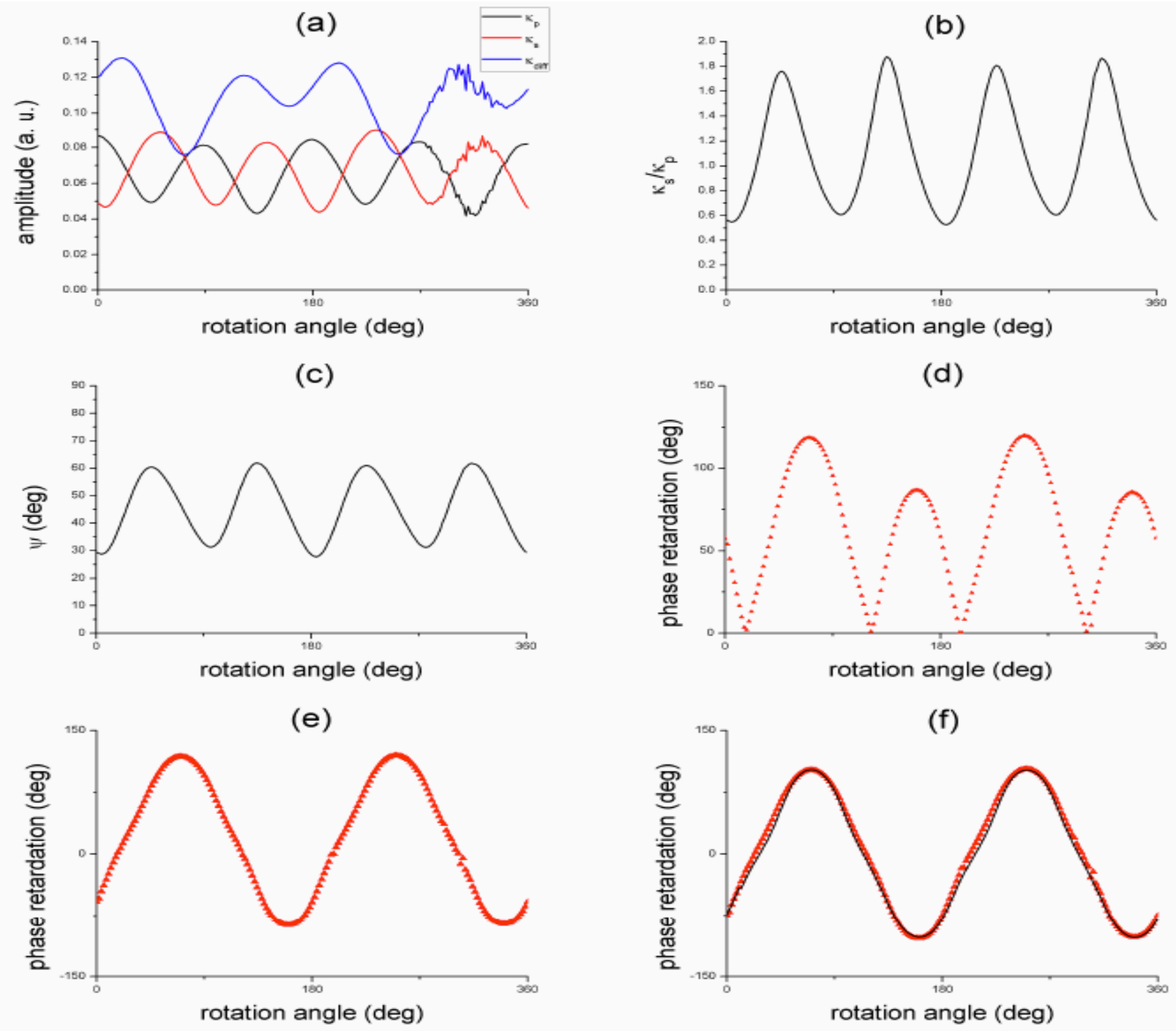
$$\psi = \tan^{-1}\left(\frac{\kappa_S}{\kappa_P}\right).$$

Experiment setup



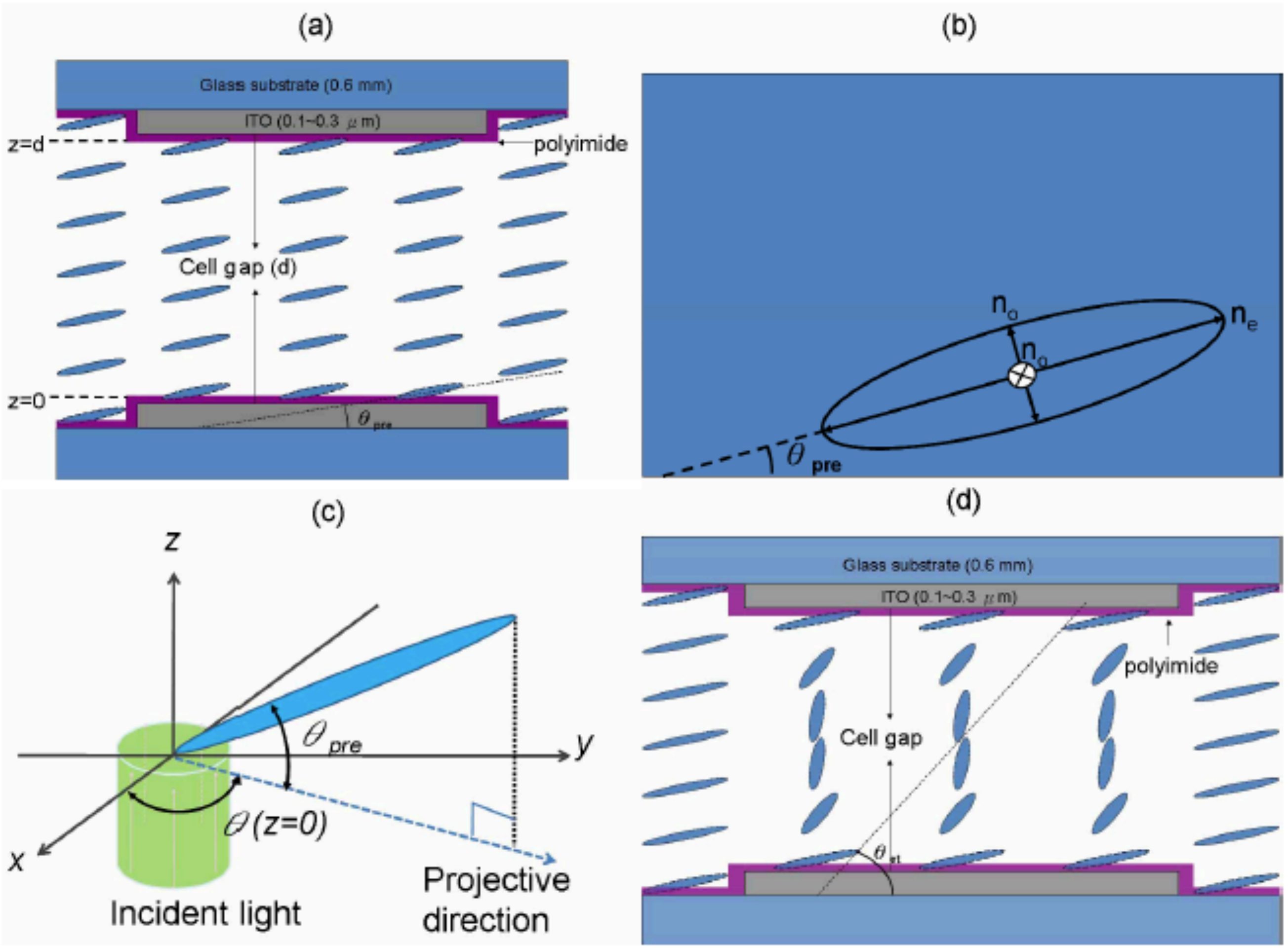
Results

Sample1: QWP

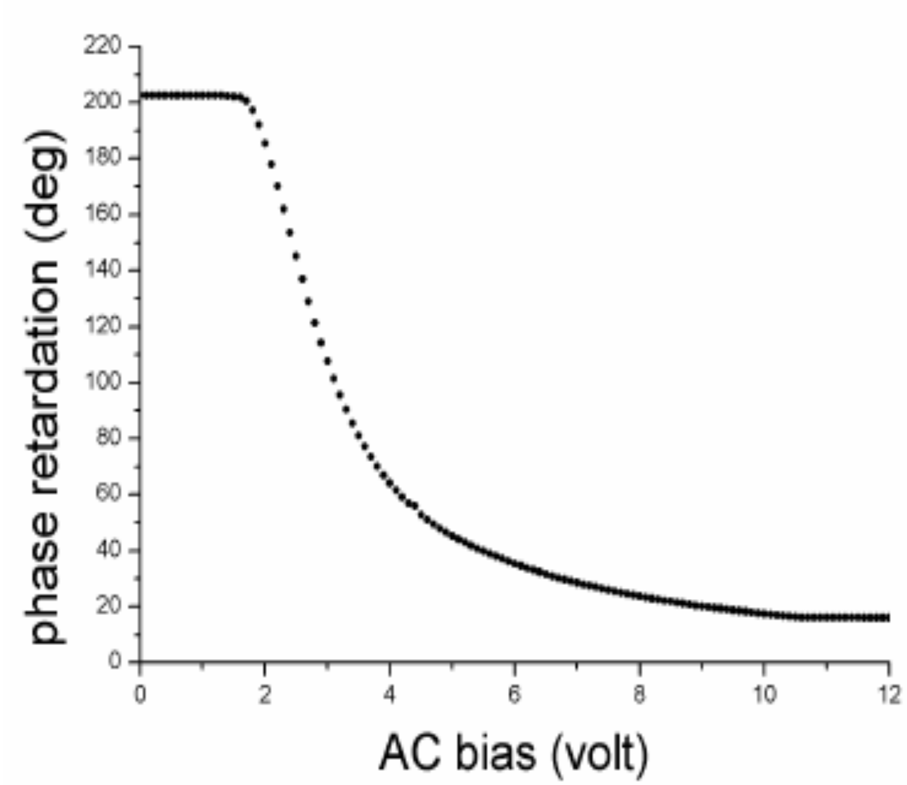


Results

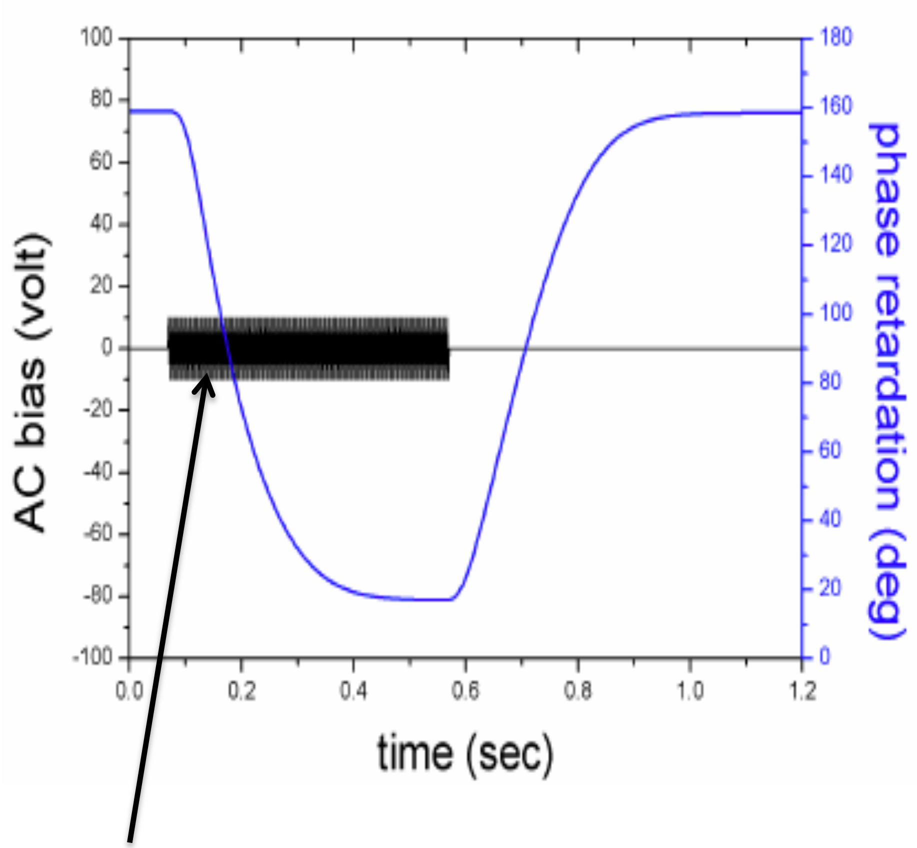
Sample2: Parallel aligned liquid crystal device (PALCD)



Results



phase retardation (deg)
AC bias (volt)



AC bias (volt)
phase retardation (deg)
time (sec)
1kHz square wave

Summary

- high-speed interferometric ellipsometer not only able to measure ellipsometric parameters in real time but also to relax the requirement of equal amplitude of two polarized heterodyne signals.

- Determination of retardation parameters of multiple-order wave plate using a phase-sensitive heterodyne ellipsometer

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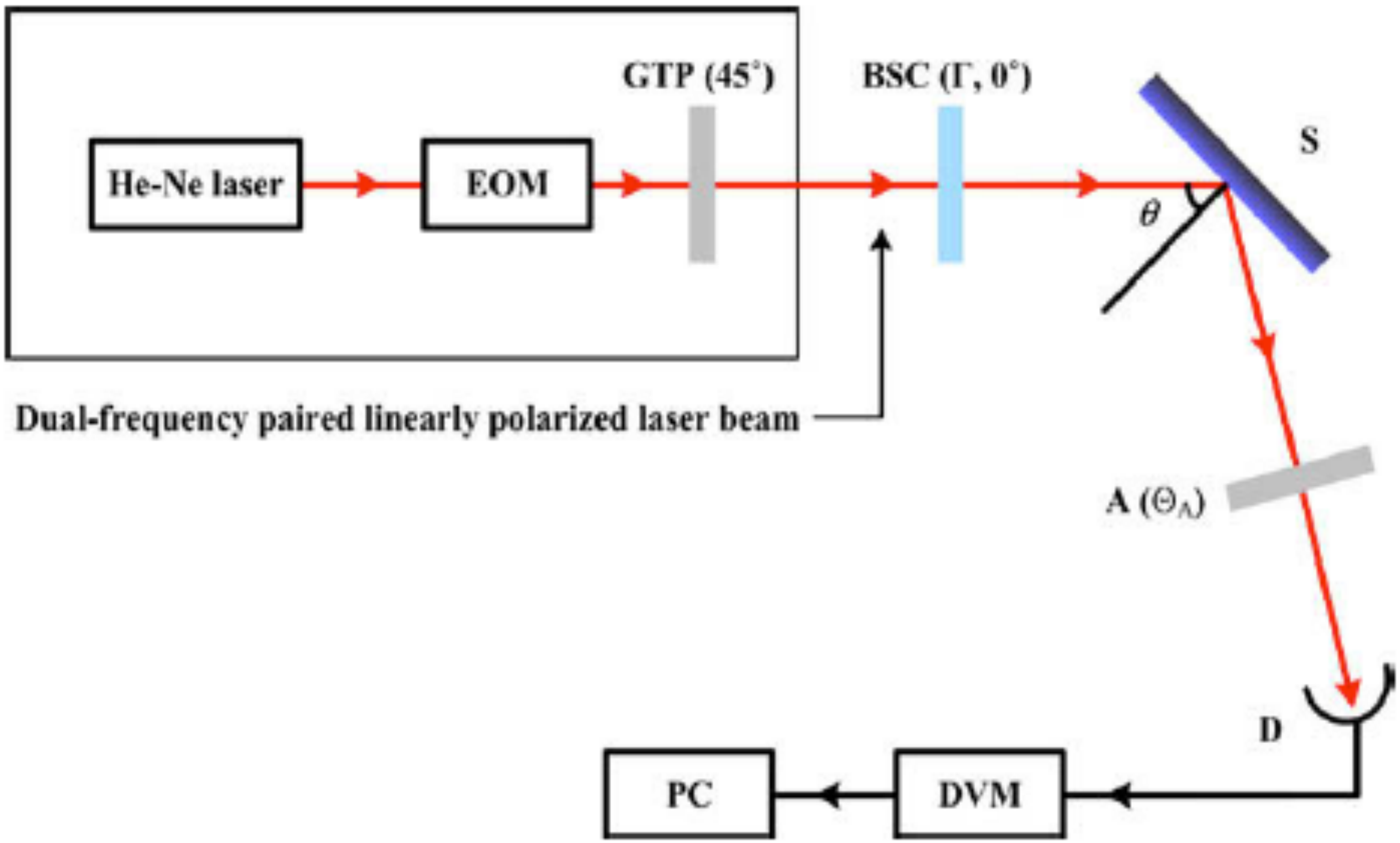
Experiment setup



Dual frequency laser

- Linearly polarized light

$$\mathbf{E}_{\mathbf{L}} = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix} a \exp(i\omega_0 t)$$

- Applied a sawtooth wave for EOM

$$\Gamma = \frac{2\pi}{T}(t - mT) + \Gamma_0 + \frac{\pi}{V_\pi}(V_{\text{bias}} - V_\pi) = \omega t - 2m\pi + \Gamma_{\text{bias}},$$

$$\Gamma_{\text{bias}} = \Gamma_0 + \frac{\pi}{V_\pi}(V_{\text{bias}} - V_\pi), \quad \longrightarrow \quad 0$$

Dual frequency laser

- With sawtooth wave

$$\Gamma = \omega t - 2m\pi$$

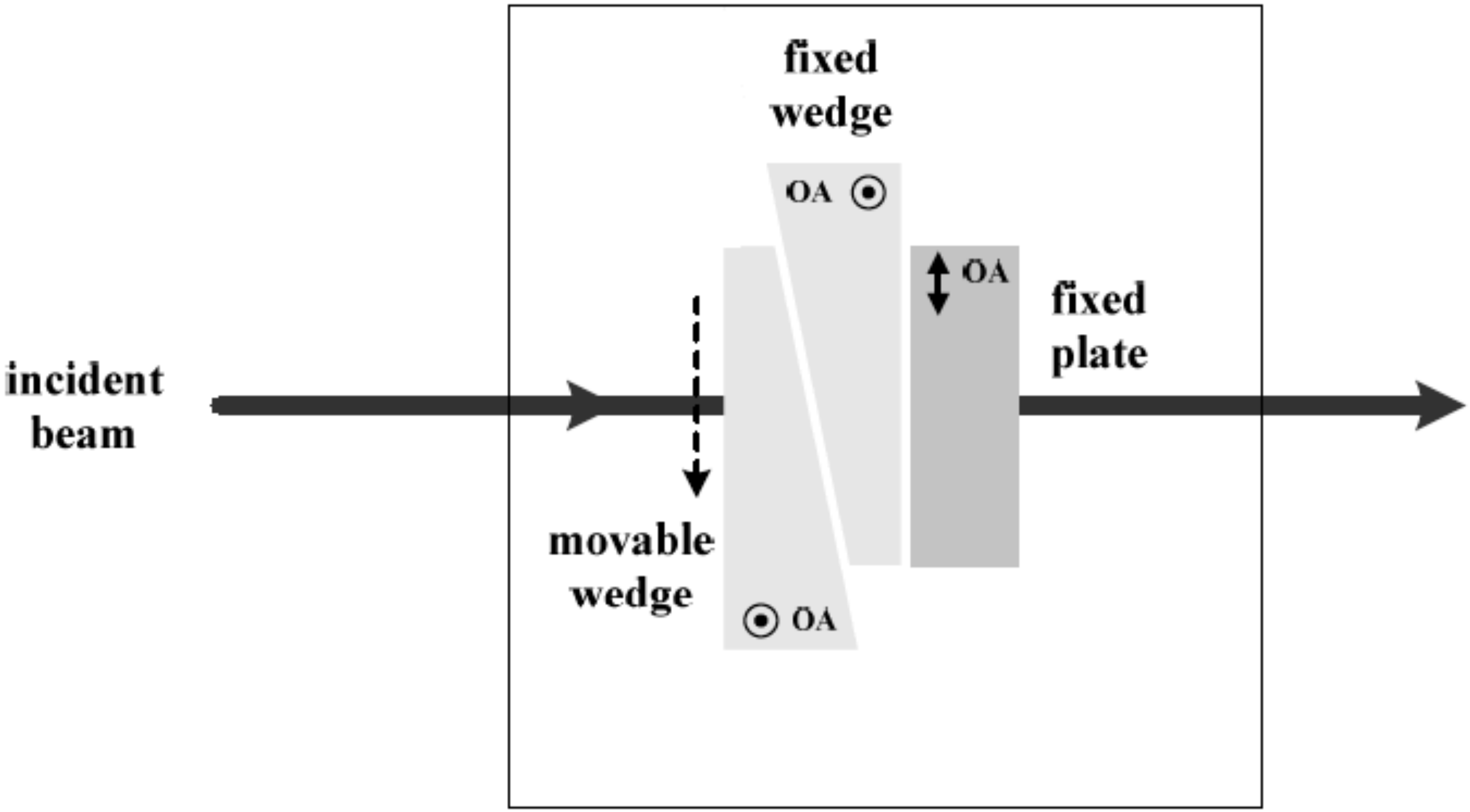
$$\mathbf{J}_{\mathbf{EOM}}(\omega t) = \exp(-im\pi)\begin{pmatrix} \exp(i\omega t/2) & 0 \\ 0 & \exp(-i\omega t/2) \end{pmatrix}$$

⬇

$$\mathbf{E}_{\mathrm{p}} = \frac{a}{\sqrt{2}}\begin{pmatrix} 1 \\ 0 \end{pmatrix}\exp(i\omega_{\mathrm{p}}t) = \frac{a}{\sqrt{2}}\begin{pmatrix} 1 \\ 0 \end{pmatrix}\exp\left[i\left(\omega_0 + \frac{\omega}{2}\right)t\right],$$

$$\mathbf{E}_{\mathrm{s}} = \frac{a}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \end{pmatrix}\exp(i\omega_{\mathrm{s}}t) = \frac{a}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \end{pmatrix}\exp\left[i\left(\omega_0 - \frac{\omega}{2}\right)t\right]。$$

Babinet Soleil compensator (BSC)



Method

- The Mueller matrices of BSC and analyzer are expressed as

$$\mathbf{M}_{\mathrm{BSC}} = T_{\mathrm{BSC}} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\Gamma & \sin\Gamma \\ 0 & 0 & -\sin\Gamma & \cos\Gamma \end{pmatrix},$$

$$\mathbf{M}_{\mathrm{A}} = T_{\mathrm{A}} \begin{pmatrix} 1 & \cos 2\Theta_{\mathrm{A}} & \sin 2\Theta_{\mathrm{A}} & 0 \\ \cos 2\Theta_{\mathrm{A}} & \cos^2 2\Theta_{\mathrm{A}} & \sin 2\Theta_{\mathrm{A}} \cos 2\Theta_{\mathrm{A}} & 0 \\ \sin 2\Theta_{\mathrm{A}} & \sin 2\Theta_{\mathrm{A}} \cos 2\Theta_{\mathrm{A}} & \sin^2 2\Theta_{\mathrm{A}} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}.$$

- A dual-frequency paired linearly polarized laser beam, which can be expressed by Stokes vector as: $\mathbf{S}_{\mathrm{DL}} = (1 \quad 0 \quad 1 \quad 0)^{\mathrm{T}} I_0 (1 + \cos\omega t)$

$$\mathbf{S}_{\mathrm{out}} = \mathbf{M}_{\mathrm{A}} \mathbf{M}_{\mathrm{S}} \mathbf{M}_{\mathrm{BSC}} \mathbf{S}_{\mathrm{DL}}, \Rightarrow \tilde{I} = T I_0 [1 - \cos 2\psi \cos 2\Theta_{\mathrm{A}} + \sin 2\psi \cos(\Delta + \Gamma) \sin 2\Theta_{\mathrm{A}}],$$

Method

- If Γ of BSC is adjusted at 0° and Θ_A is set either at 0° or 90° then:

$$\tilde{I}_p = 2\Pi_0 \sin^2\psi, \quad \text{at } \Theta_A = 0°,$$
$$\tilde{I}_s = 2\Pi_0 \cos^2\psi, \quad \text{at } \Theta_A = 90°,$$

and

$$\psi = \tan^{-1}\left(\tilde{I}_p/\tilde{I}_s\right)^{1/2}.$$

Method

- Similarly, when the analyzer is set at 45°

$$\tilde{I}_{45^\circ} = T_0 I_0[1 + \sin 2\psi \cos(\Delta + \Gamma)],$$

- Thus, Δ can be obtained by shifting the phase retardation Γ of BSC at 0, 90, 180, and 270 sequentially.

$$\tilde{I}_1 = T_0 I_0(1 + \sin 2\psi \cos \Delta), \quad \text{at } \Gamma = 0^\circ,$$
$$\tilde{I}_2 = T_0 I_0(1 - \sin 2\psi \sin \Delta), \quad \text{at } \Gamma = 90^\circ,$$
$$\tilde{I}_3 = T_0 I_0(1 - \sin 2\psi \cos \Delta), \quad \text{at } \Gamma = 180^\circ,$$
$$\tilde{I}_4 = T_0 I_0(1 + \sin 2\psi \sin \Delta), \quad \text{at } \Gamma = 270^\circ.$$

➡

$$\alpha = \frac{\tilde{I}_1 - \tilde{I}_3}{\tilde{I}_1 + \tilde{I}_3} = \sin 2\psi \cos \Delta,$$
$$\beta = \frac{\tilde{I}_4 - \tilde{I}_2}{\tilde{I}_4 + \tilde{I}_2} = \sin 2\psi \sin \Delta,$$

➡ $$\Delta = \tan^{-1}(\beta/\alpha).$$

Results

- The calibrated step wafer in which the silicon dioxide thin film (Mikropack ID0153).

Area	Ellipsometric parameters		Thickness
	ψ (°)	Δ (°)	T (nm)
#3: Measured	11.14	162.42	290.95
#3: Calibrated	10.83	162.23	290.16
#4: Measured	38.93	280.26	187.96
#4: Calibrated	38.30	280.06	189.20

Summary

- The phase shifting technique integrated into DPPSE fully expands the dynamic range of EP. This overcomes the limitation of conventional ellipsometer based on intensity modulation in measurement