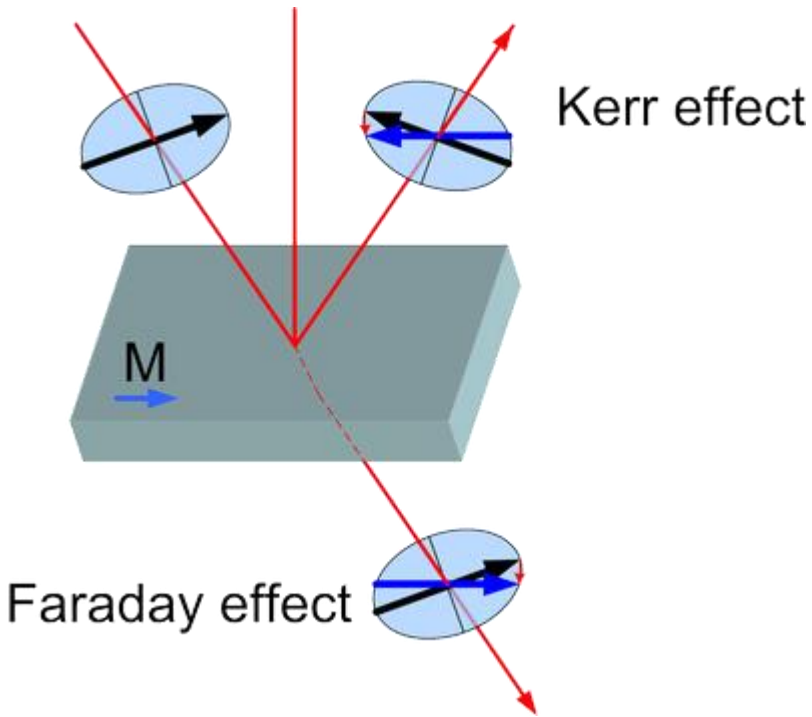
Precision Optical Rotation Measurements

Seoncheol Cha

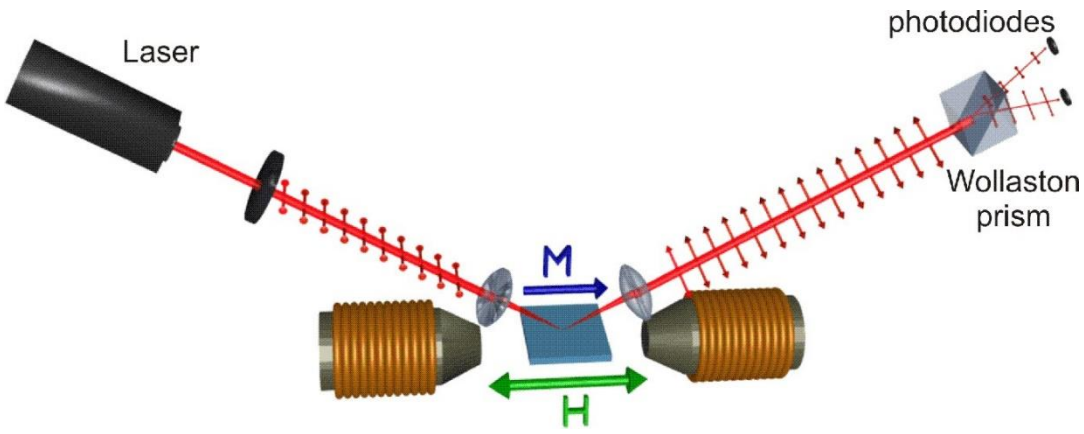
Soft matter optical spectroscopy

2014.7.25

Magneto-optics effects



Measurements of Magneto-optic Kerr effects



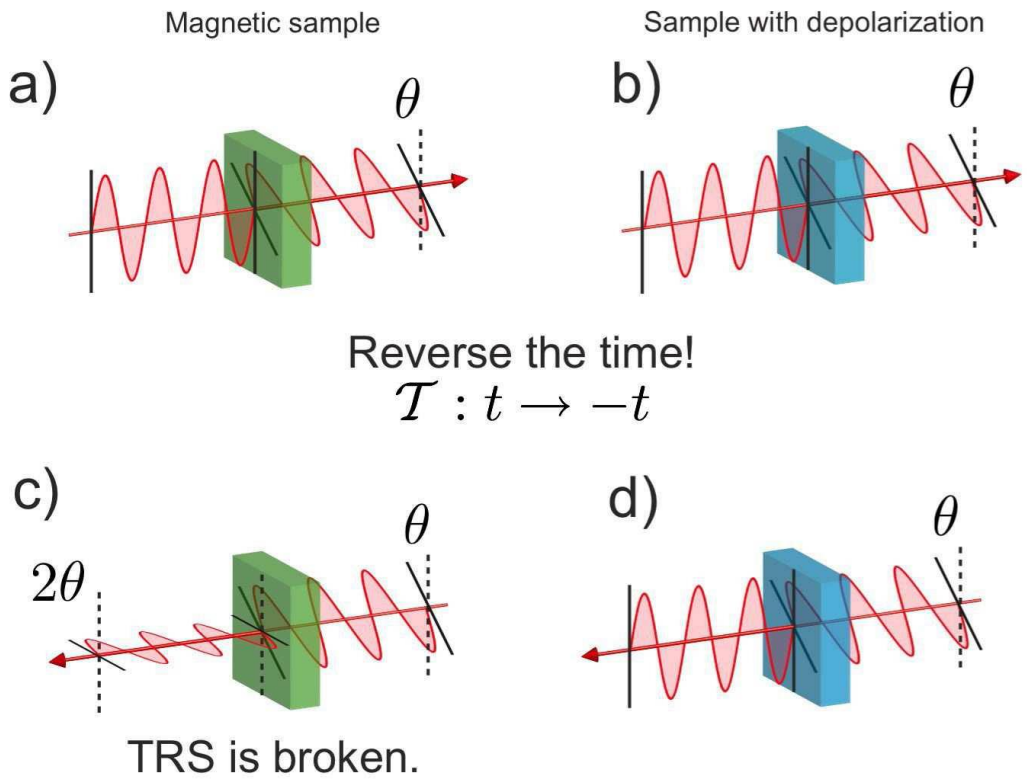
→ Not very accurate !

Magneto-optical Kerr effect
On Rotation of the Plane of the Polarization by Reflection from the Pole of a Magnet (1877)

$\neq$

Kerr effect (quadratic-optic effects)
A new relation between electricity and light: Dielectrified media birefringent (1875)

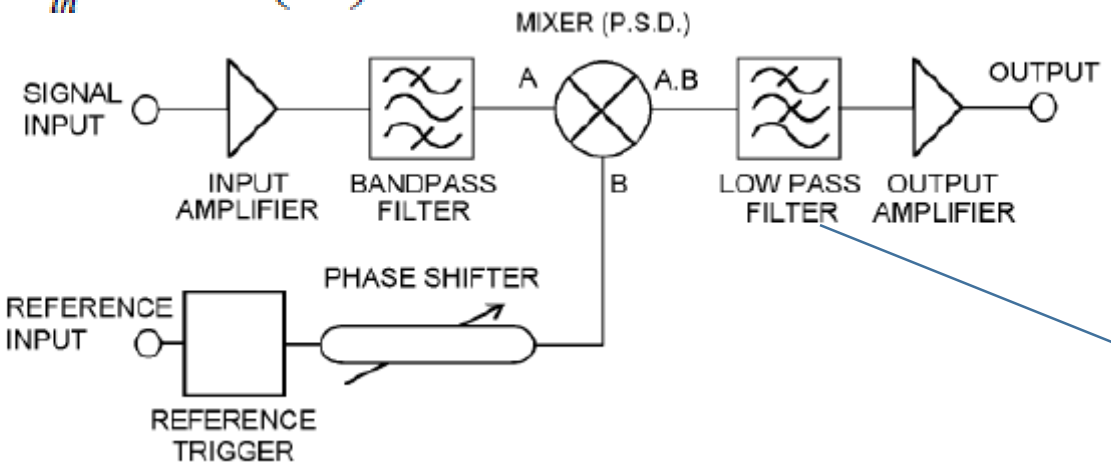
Time-reversal Breaking in Magneto-optics effects



SLAC-PUB-14083

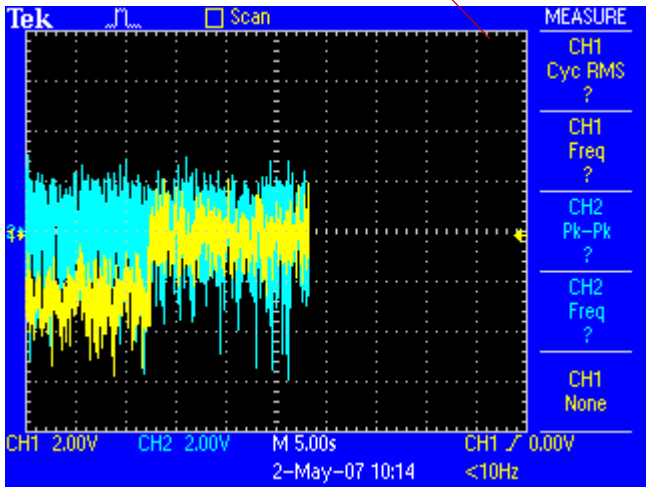
Phase Sensitive detection

$$V_{in} = A\cos(\omega t)$$



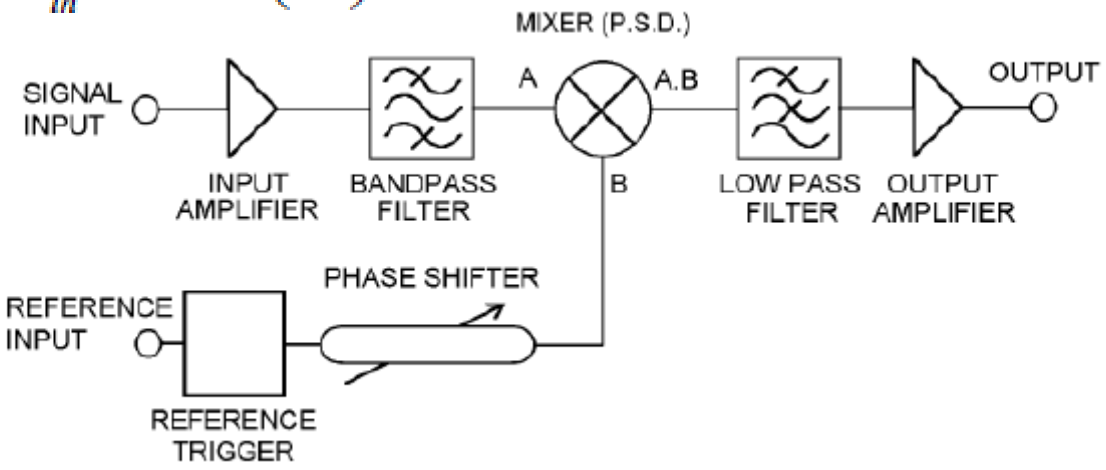
$$V_{ref} = B\cos(\omega t + \phi)$$

$$\begin{aligned}
V_{in} &= A\cos(\omega t)\cdot B\cos(\omega t+\phi) \\
&= AB\cos\omega t\cdot(\cos\omega t\cos\phi - \sin\omega t\sin\phi) \\
&= AB(\cos^2\omega t\cos\phi - \cos\omega t\sin\omega t\sin\phi) \\
&= AB\{(\tfrac{1}{2}+\tfrac{1}{2}\cos 2\omega t)\cos\phi - \tfrac{1}{2}\sin 2\omega t\sin\phi\} \\
&= \tfrac{1}{2}AB\{(1+\cos 2\omega t)\cos\phi - \sin 2\omega t\sin\phi\} \\
&= \tfrac{1}{2}AB\{\cos\phi + \cos 2\omega t\cos\phi - \sin 2\omega t\sin\phi\} \\
&= \tfrac{1}{2}AB\cos\phi + \tfrac{1}{2}AB(\cos 2\omega t\cos\phi - \sin 2\omega t\sin\phi) \\
&= \tfrac{1}{2}AB\cos\phi + \boxed{\tfrac{1}{2}AB\cos(2\omega t+\phi)}
\end{aligned}$$



Phase Sensitive detection for Faraday rotation

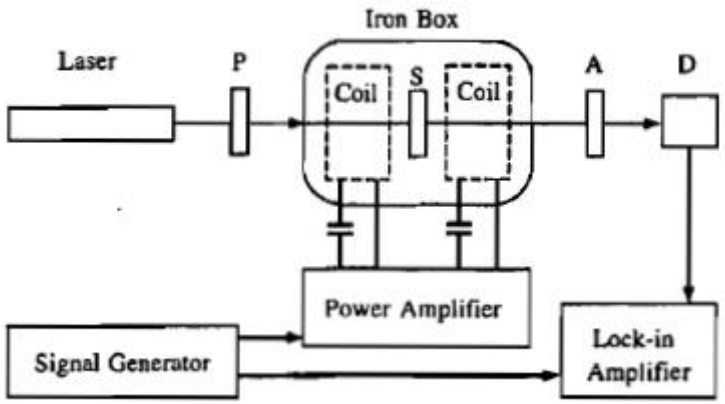
$$V_{in} = A\cos(\omega t)$$



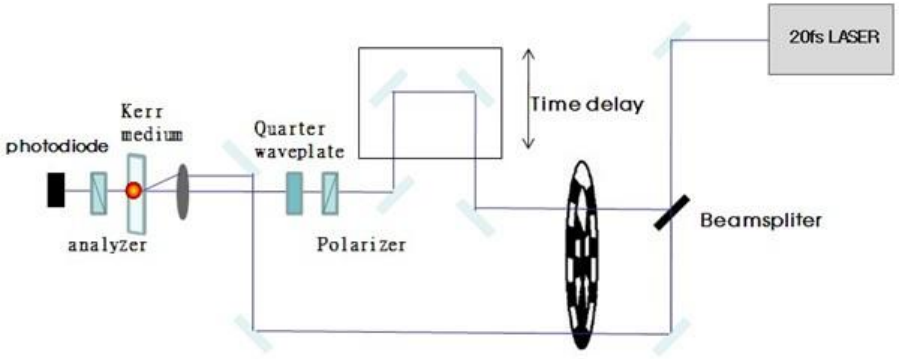
$$V_{ref} = B\cos(\omega t + \phi)$$

$$= \tfrac{1}{2}AB\cos\phi + \tfrac{1}{2}AB\cos(2\omega t + \phi)$$

Faraday rotation measurements
By modulating magnetic field



OKE measurements
By modulating pump intensity

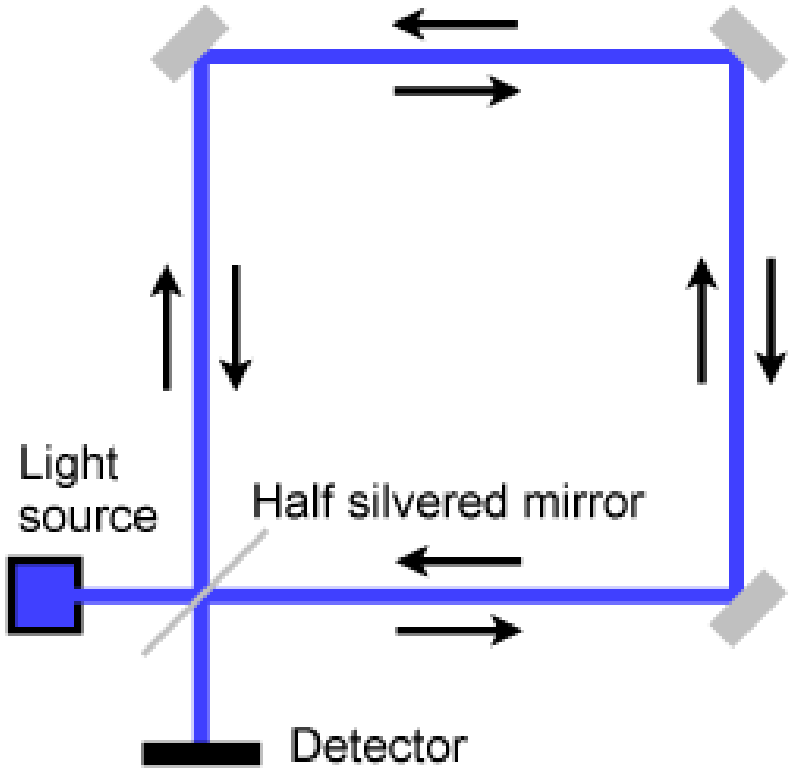


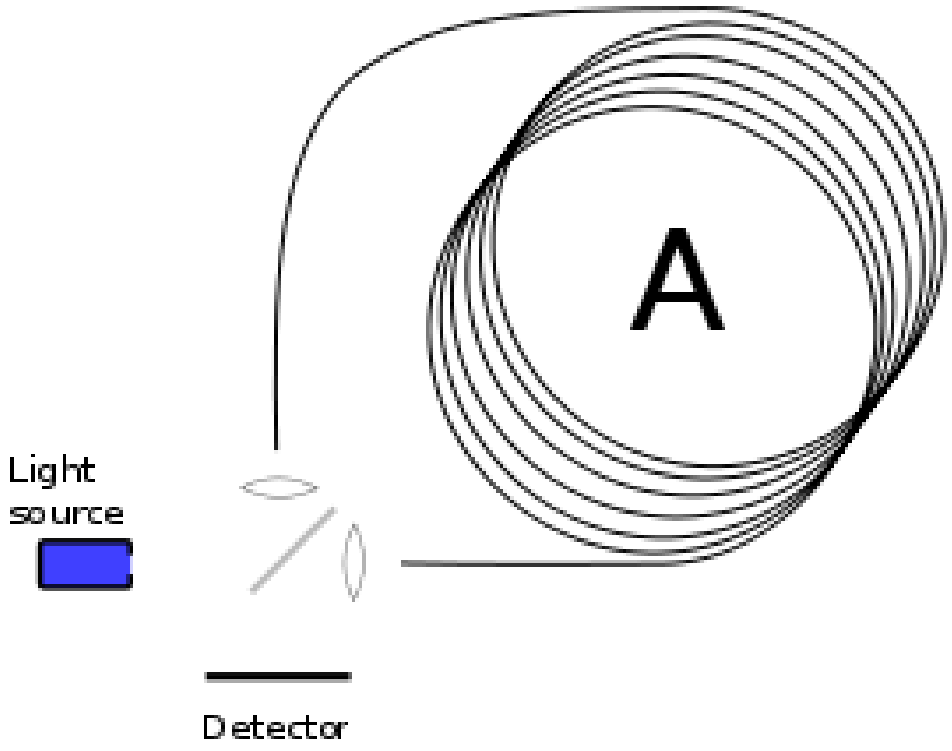
Mira Seed Laser : Autocorrelation width ~20fs , Tuning range 780~840nm
Lock-in : stanford research SR850
Time delay stage resolution : 0.1um
Choppor : tholab two frequency chopor (in:out=5:7)

Sagnac interferometry

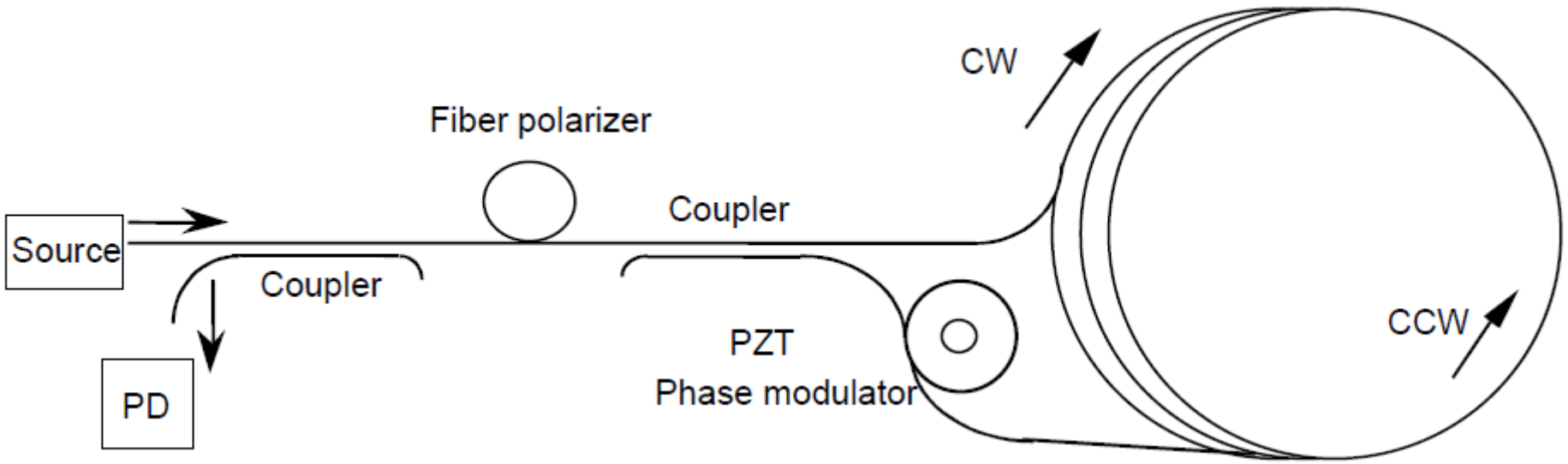
Geroge Sagnac (1913)

wikipedia





Sagnac interferometry with phase modulation



$$\phi_{ccw} - \phi_{cw} = \phi_s + \phi(t) - \phi(t+\tau)$$

$$\phi_{ccw} - \phi_{cw} = \phi_s + \phi\left(t - \frac{\tau}{2}\right) - \phi(t + \frac{\tau}{2}) \qquad \phi(t) = \phi_{mo} cos\omega_m t$$

$$\phi_{ccw} - \phi_{cw} = \phi_s + 2\phi_{mo} sin\omega_m \left(\frac{\tau}{2}\right) sin\omega_m t = \phi_s + \phi_m sin\omega_m t$$

$$\frac{I}{I_0} = 1 + \left[J_0(\Phi_m) + 2\sum_{k-1}^{\infty} J_{2k}(\Phi_m) cos2k\omega_m t\right] cos\phi_s + \left[2\sum_{k-1}^{\infty} J_{2k-1}(\Phi_m) \cos(2k-1)\omega_m t\right] sin\phi_s$$

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Modified Sagnac interferometer for high-sensitivity magneto-optic measurements at cryogenic temperatures

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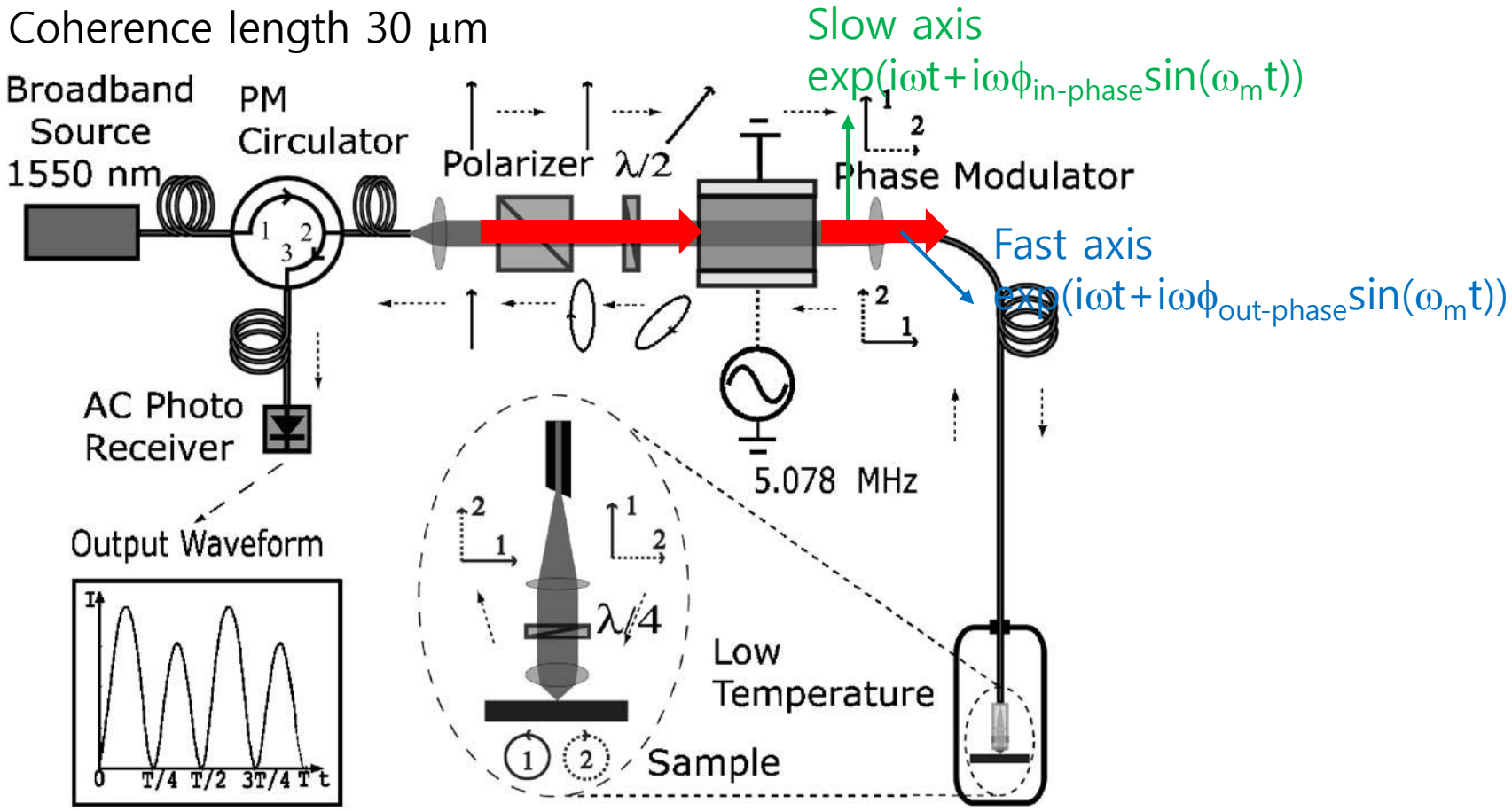
Sagnac interferometer for magneto optic measurements

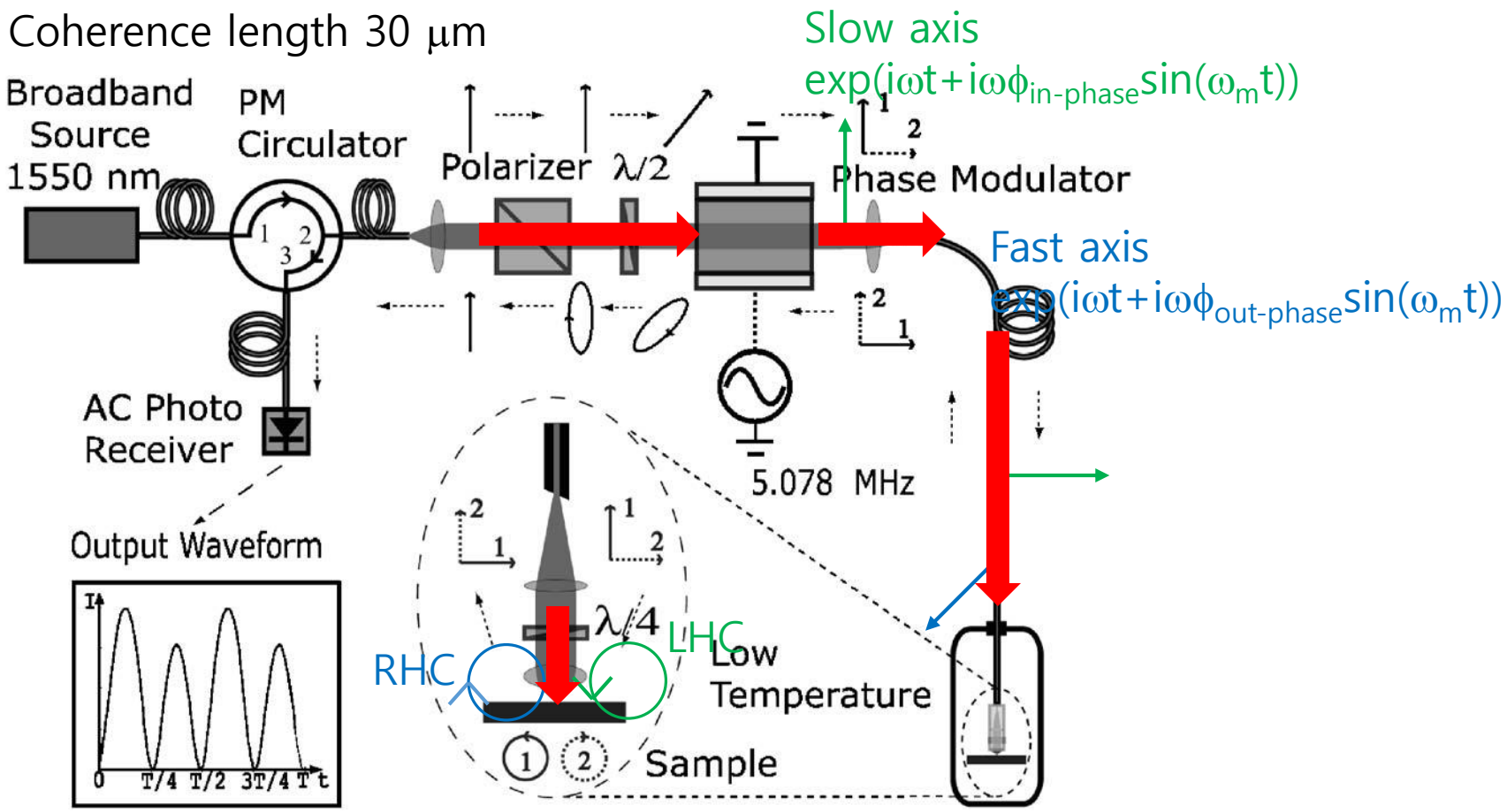
Coherence length 30 μm



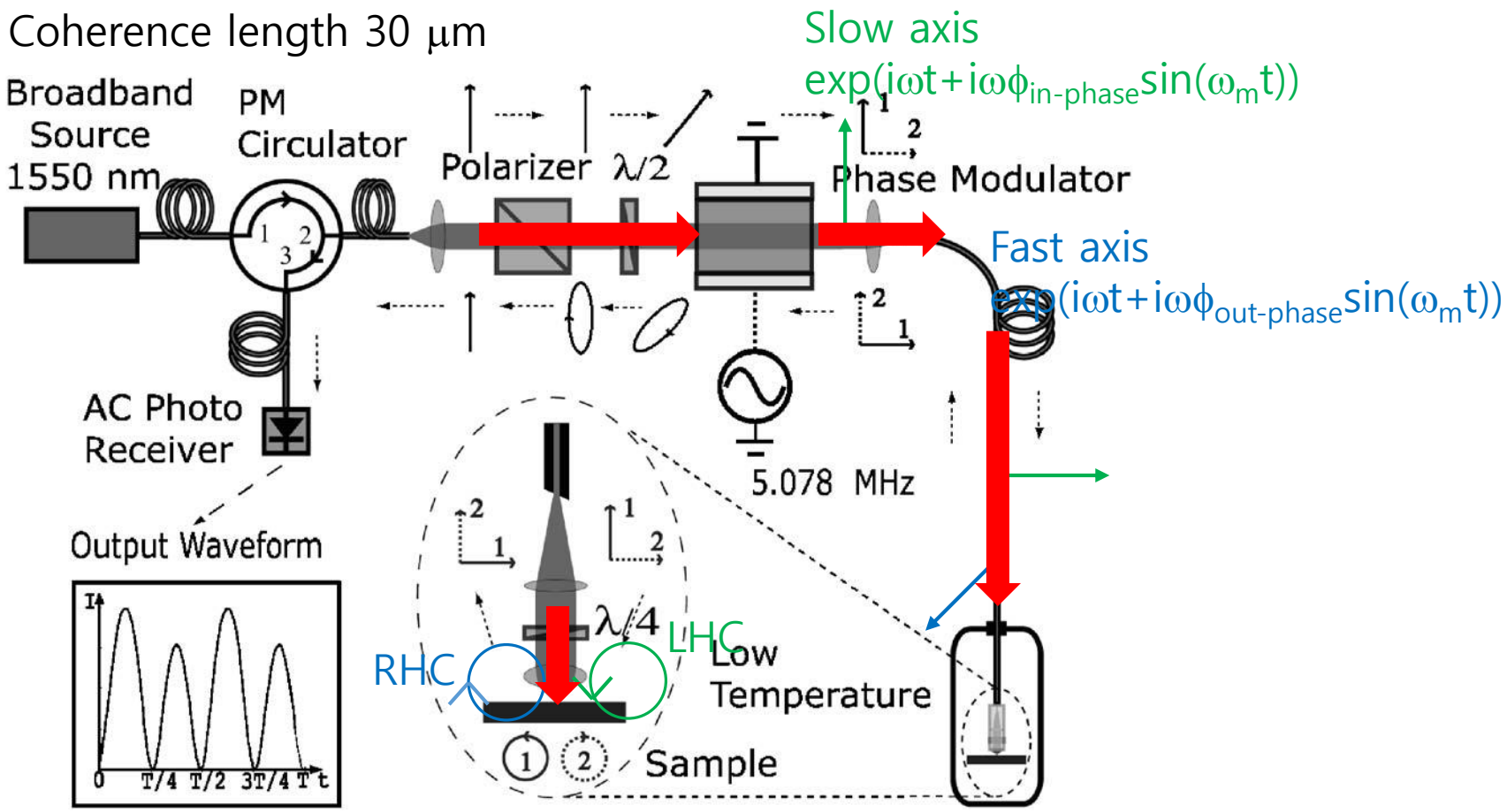
50 mm $LiNbO_3$
Negative uniaxial
n_o = 2.21
n_e = 2.13 at 1.55 μm
5.078 MHz modulation

Optical path difference
(n_o – n_e) * 50 mm
~ 4 mm
>>
Coherence length 30 μm

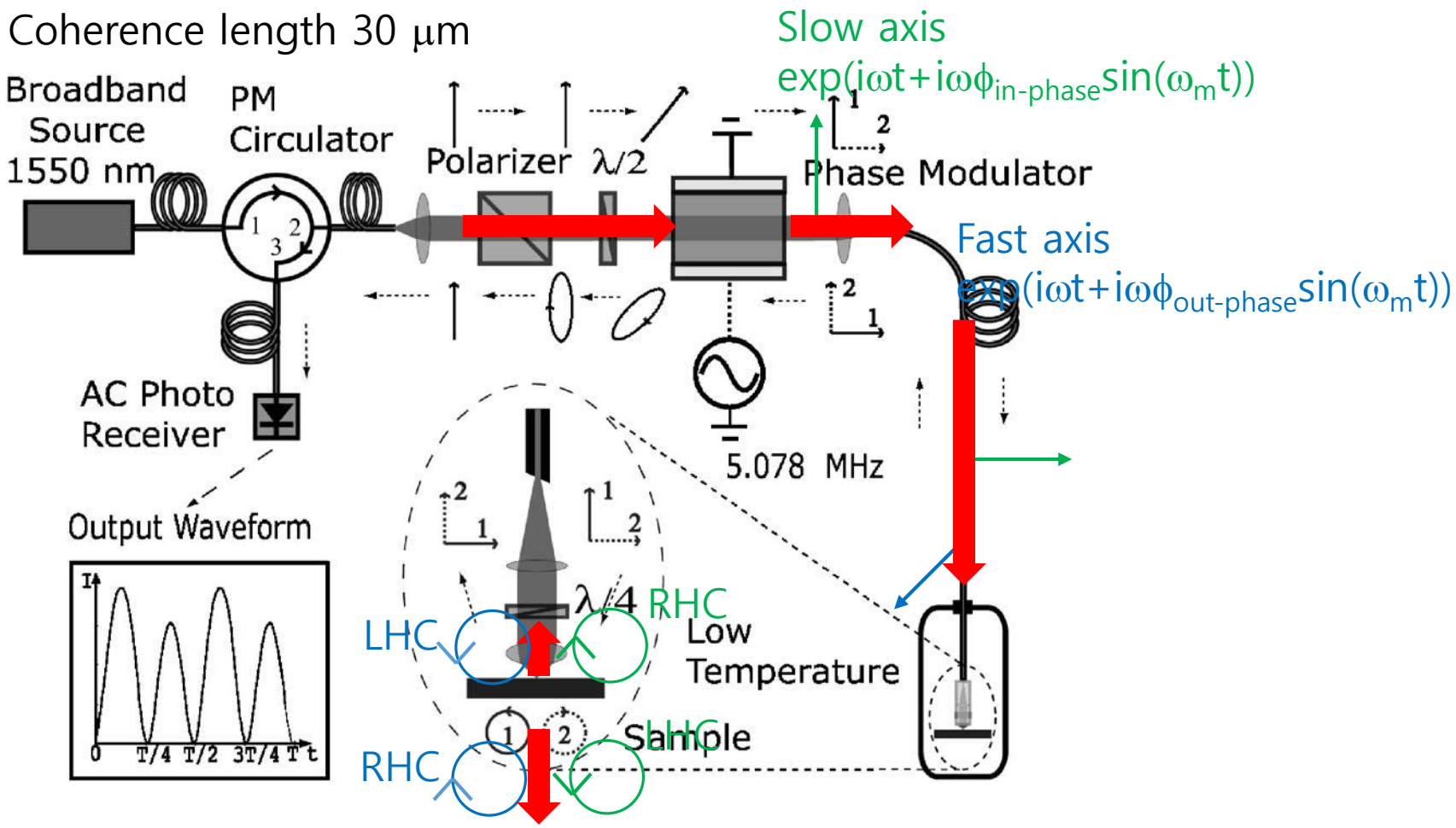
Sagnac interferometer for magneto optic measurements



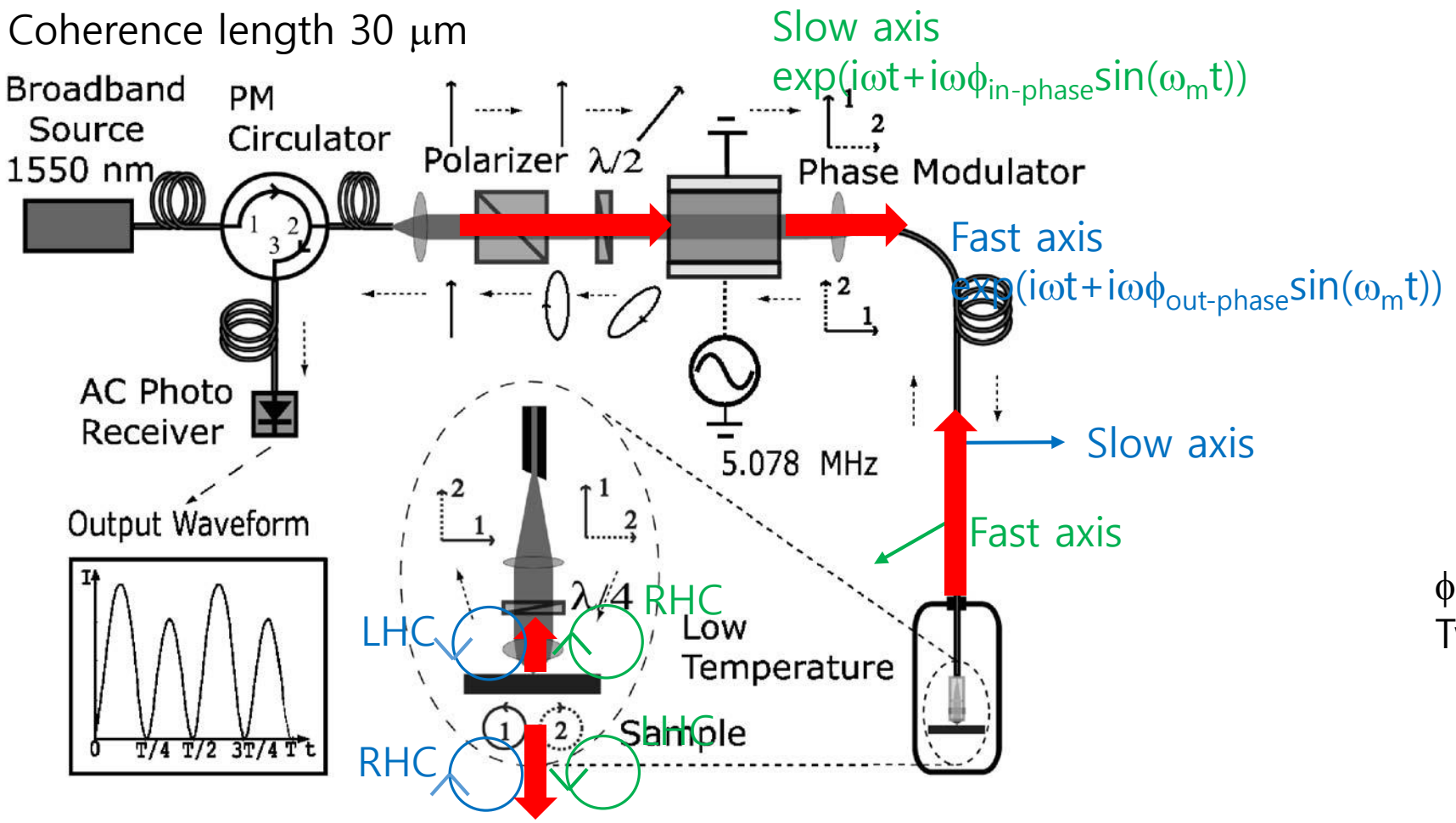
Sagnac interferometer for magneto optic measurements



Sagnac interferometer for magneto optic measurements



Sagnac interferometer for magneto optic measurements



$\phi_{nr} = 2\theta_K$

Twice of Kerr rotation

Sagnac interferometer for magneto optic measurements

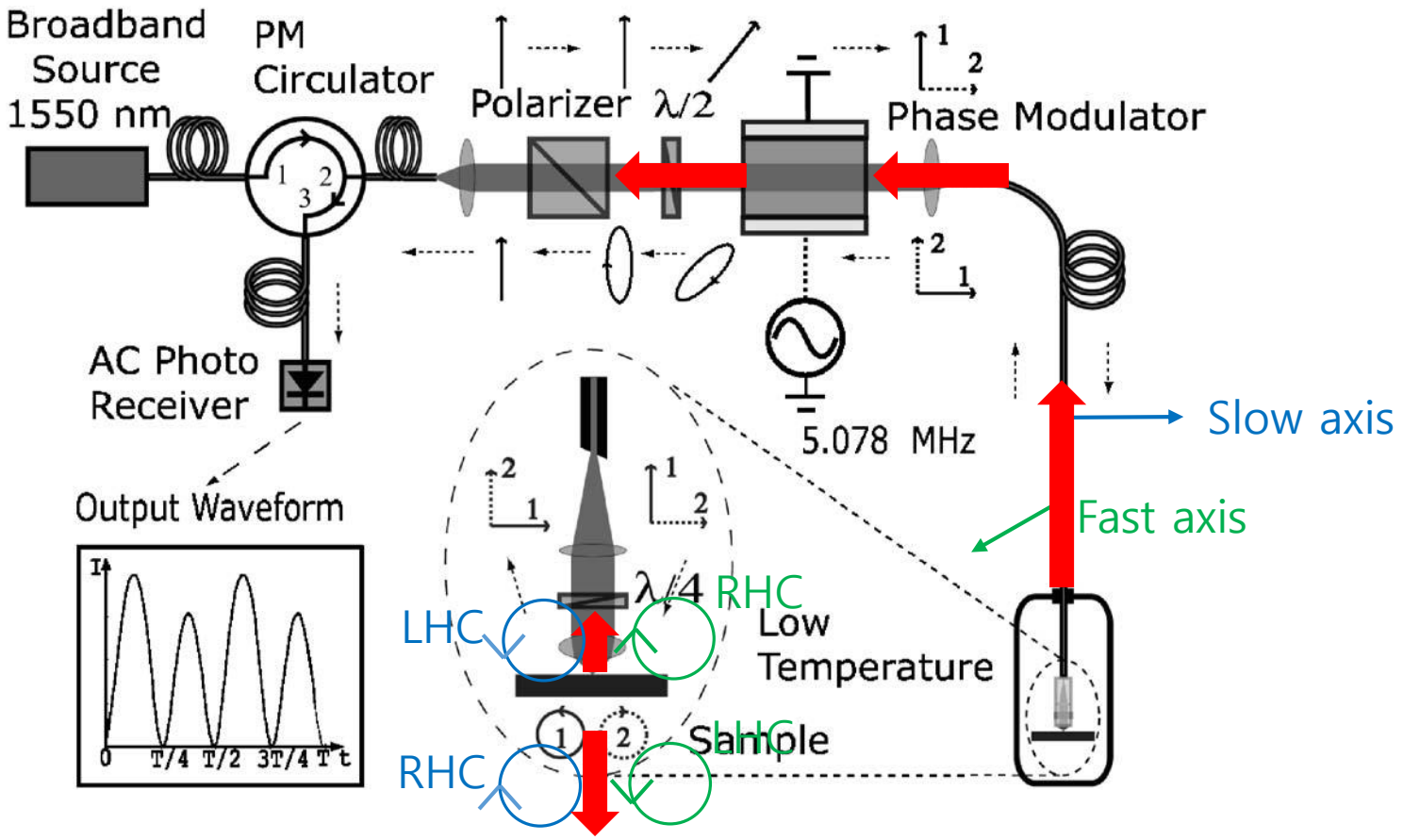
Slow axis

$\exp(i\omega t + i\omega\phi_{out\text{-}phase}\sin(\omega_m t) + i\omega\phi_{in\text{-}phase}\sin(\omega_m(t+\tau)))$

Fast axis

$\exp(i\omega t + i\omega\phi_{in\text{-}phase}\sin(\omega_m t) + i\omega\phi_{out\text{-}phase}\sin(\omega_m(t+\tau)))$

Coherence length 30 μm



Phase difference

$\phi_m \sin(\omega_m(t+\tau)) - \sin(\omega_m t) + 2\theta_K$

$\phi_m = \phi_{in\text{-}phase} - \phi_{out\text{-}phase} \sim 0.92$ rad

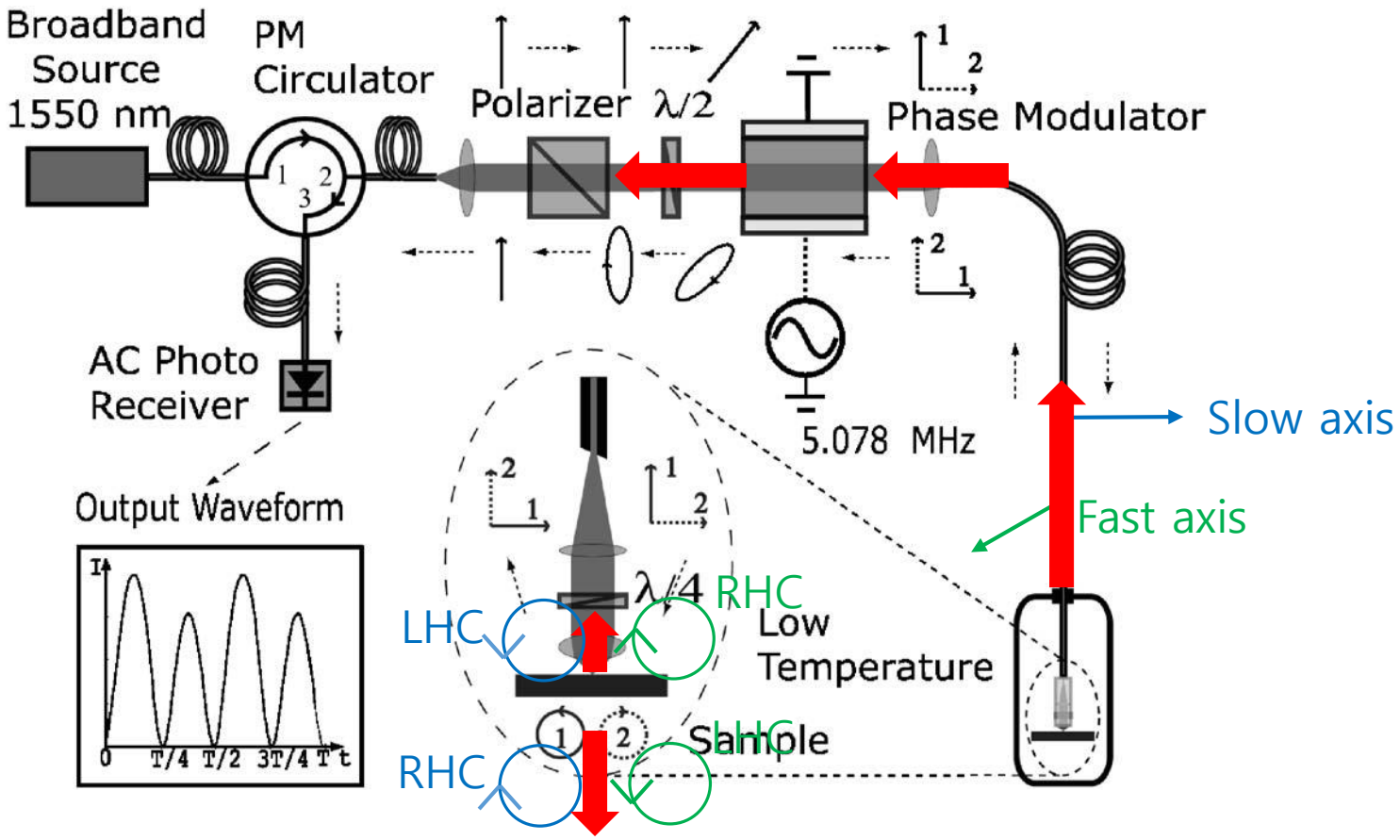
-> elliptic polarized light

$\phi_{nr} = 2\theta_K$

Twice of Kerr rotation

Sagnac interferometer for magneto optic measurements

Coherence length 30 μm



Phase difference

$\phi_m(\sin(\omega_m(t+\tau))-\sin(\omega_m t))+2\theta_K$

$\phi_m=\phi_{in\text{-}phase}-\phi_{out\text{-}phase}$ ~ 0.92 rad

$\phi_m(\sin(\omega_m(t+\tau))-\sin(\omega_m t))+2\theta_K$

$=\phi_m(\sin(\omega_m(t+\tau/2))-\sin(\omega_m t-\tau/2))+2\theta_K$

$=2\phi_m\sin(\omega_m\tau/2)\sin(\omega_m t)+2\theta_K$

$=2\phi_m\sin(\omega_m t)+2\theta_K$

where $\tau=\pi/\omega_m$

$\cos(2\theta_K+2\phi_m\sin(\omega_m t))$

$=J_0(2\phi_m)\cos(\omega_m t)$

$-J_1(2\phi_m)(\cos(2\theta_K-\omega_m t)-\cos(2\theta_K+\omega_m t))$

$+J_2(2\phi_m)(\cos(2\theta_K-2\omega_m t)+\cos(2\theta_K+2\omega_m t))$

...

$=J_0(2\phi_m)\cos(\omega_m t)$

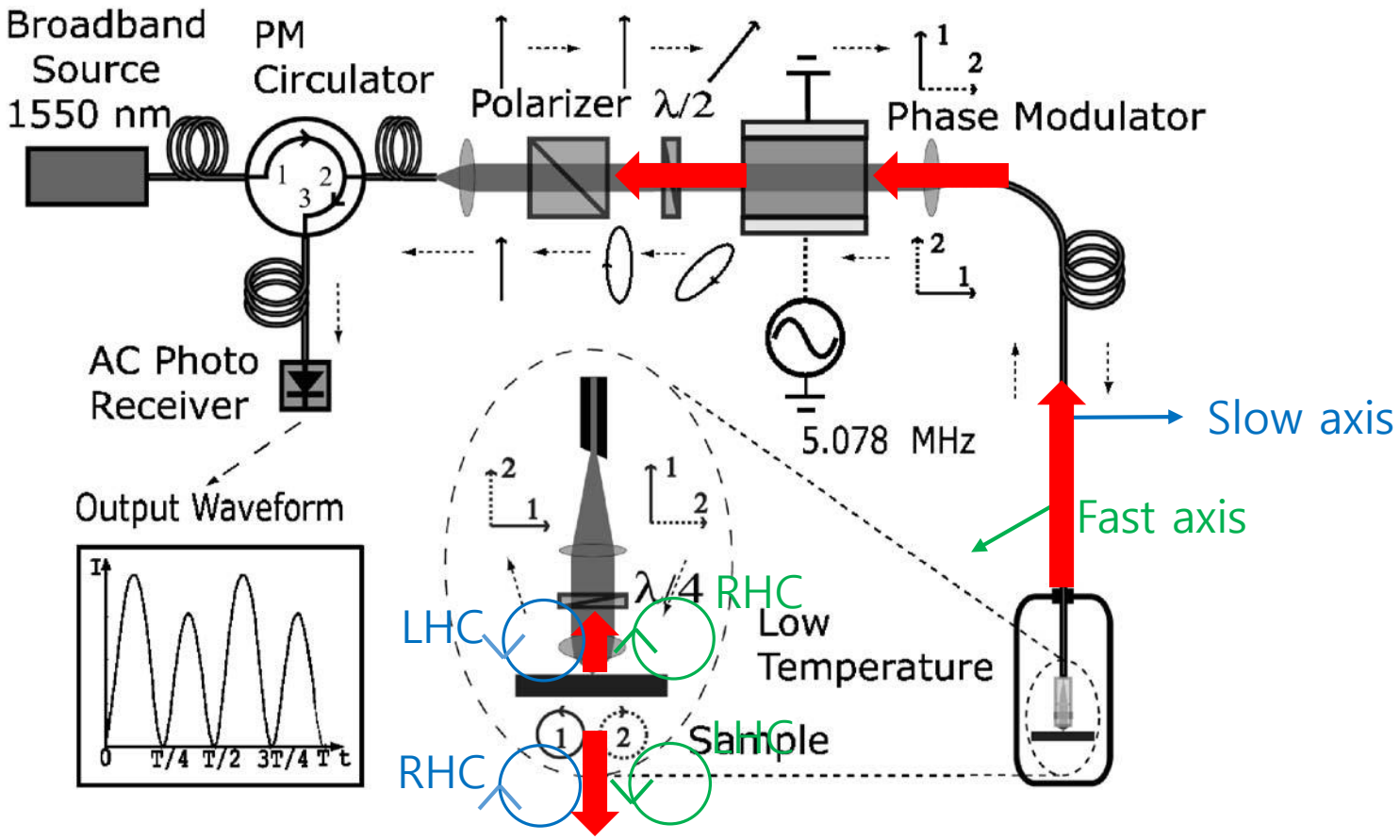
$-J_1(2\phi_m)\sin(2\theta_K)\sin(\omega_m t)$

$-J_2(2\phi_m)\cos(2\theta_K)\cos(2\omega_m t)$

...

Sagnac interferometer for magneto optic measurements

Coherence length 30 μm



$\cos(2\theta_K + 2\phi_m \sin(\omega_m t))$
$= J_0(2\phi_m)\cos(\omega_m t)$
$\quad -\mathbf{J_1(2\phi_m)\sin(2\theta_K)}\sin(\omega_m t)$
$\quad -\mathbf{J_2(2\phi_m)\cos(2\theta_K)}\cos(2\omega_m t)$
$\quad \ldots$

$I_\omega / I_{2\omega} = J_1(2\phi_m)\sin(2\theta_K)/J_2(2\phi_m)\cos(2\theta_K)$

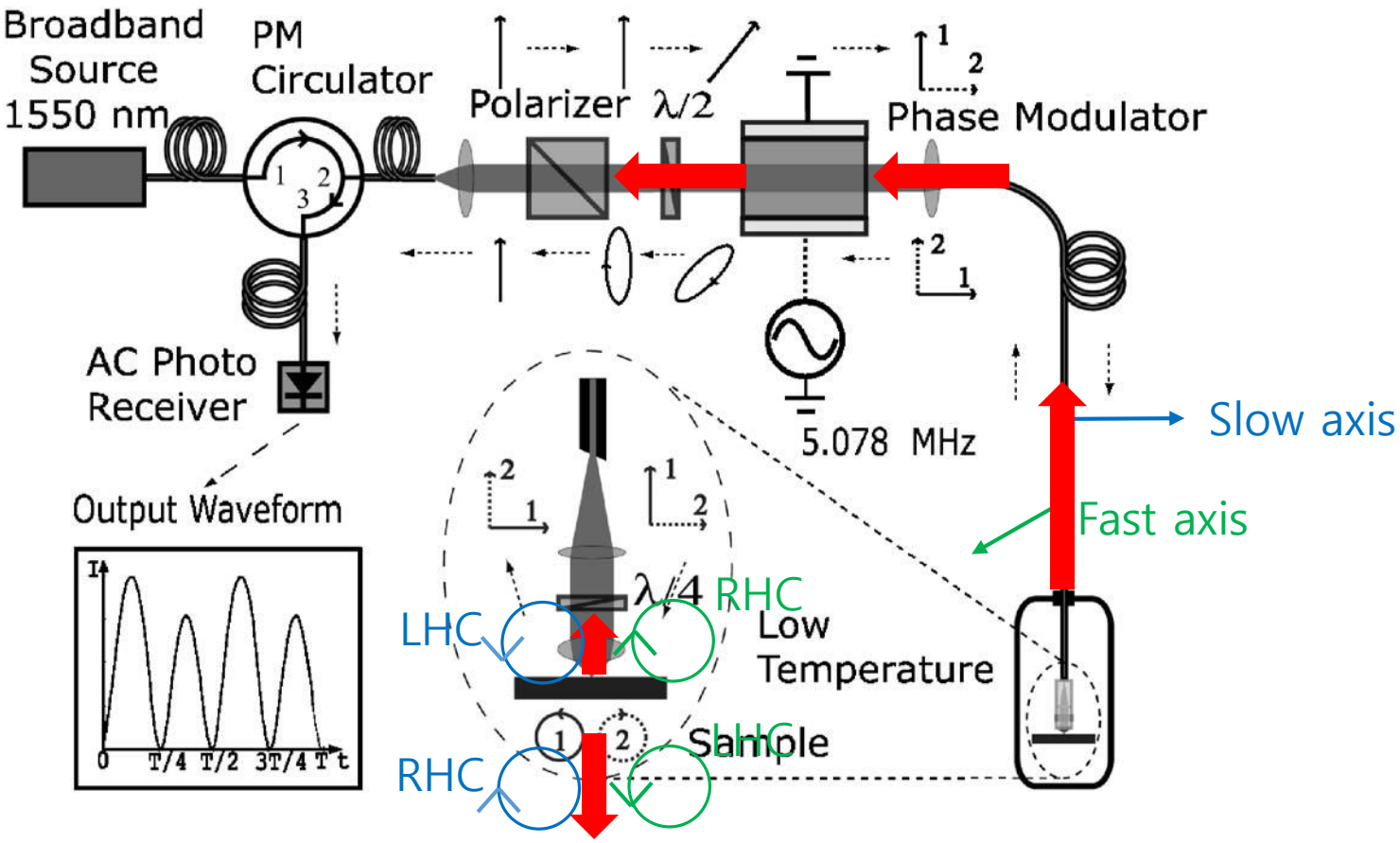
$\sin(2\theta_K)/\cos(2\theta_K) = I_\omega J_2(2\phi_m)/I_{2\omega} J_1(2\phi_m)$

$$\theta_K = \frac{1}{2}\tan^{-1}\left[\frac{J_2(2\phi_m)I_\omega}{J_1(2\phi_m)I_{2\omega}}\right]$$

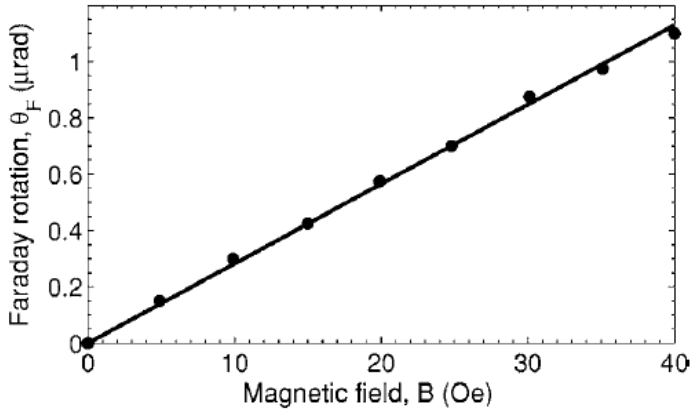
Sagnac interferometer for magneto optic measurements

$$\theta_K = \frac{1}{2}\tan^{-1}\left[\frac{J_2(2\phi_m)I_\omega}{J_1(2\phi_m)I_{2\omega}}\right]$$

Coherence length 30 μm



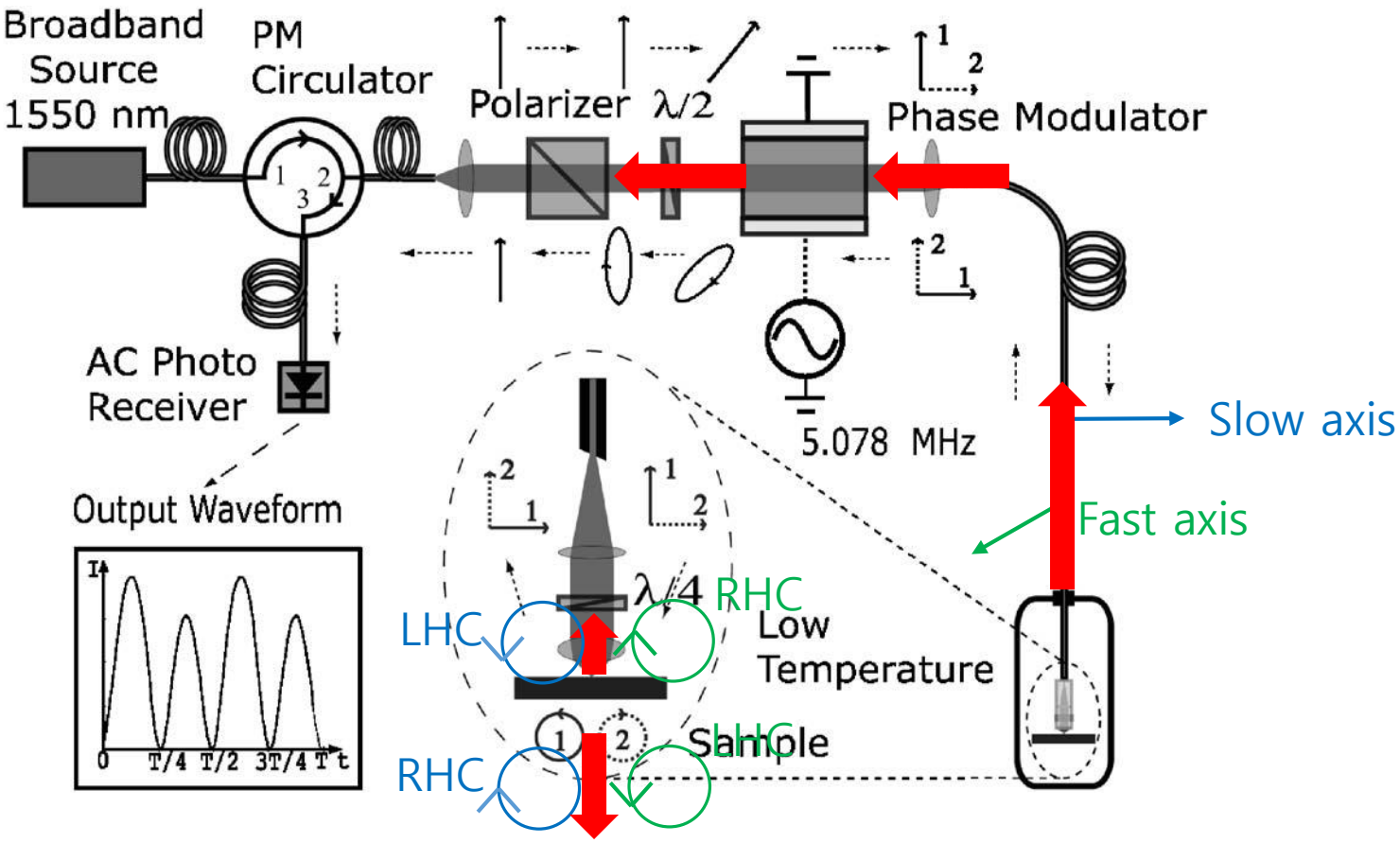
Calibration
40 μm thick bismuth-doped rare-earth iron garnet crystal - 3.3° (83° /mm)
Known value : 90°/mm



0.5 mm thick slab of fused silica
Verdet constant : 5.52 x 10^{-8} rad/Oe mm
- 5% error to literature value

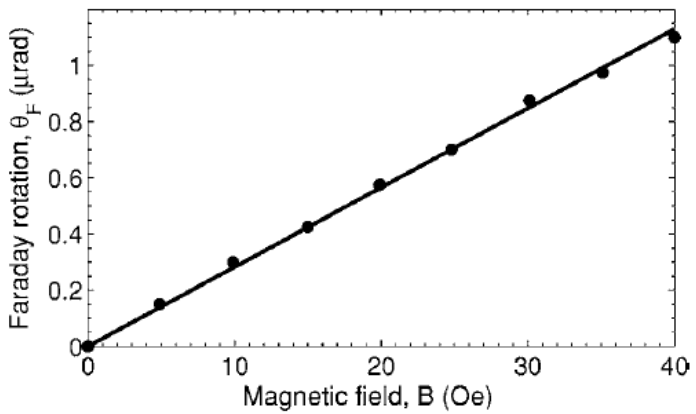
Sagnac interferometer for magneto optic measurements

Coherence length 30 μm



$$\theta_K = \frac{1}{2}\tan^{-1}\left[\frac{J_2(2\phi_m)I_\omega}{J_1(2\phi_m)I_{2\omega}}\right]$$

Calibration
40 μm thick bismuth-doped rare-earth iron garnet crystal - 3.3° (83° /mm)
Known value : 90°/mm



0.5 mm thick slab of fused silica
Verdet constant : 5.52 x 10^{-8} rad/Oe mm
- 5% error to literature value

No rotation for λ/4 plate

Sagnac interferometer for magneto optic measurements

PRL 97, 167002 (2006) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2006

High Resolution Polar Kerr Effect Measurements of Sr_2RuO_4: Evidence for Broken Time-Reversal Symmetry in the Superconducting State

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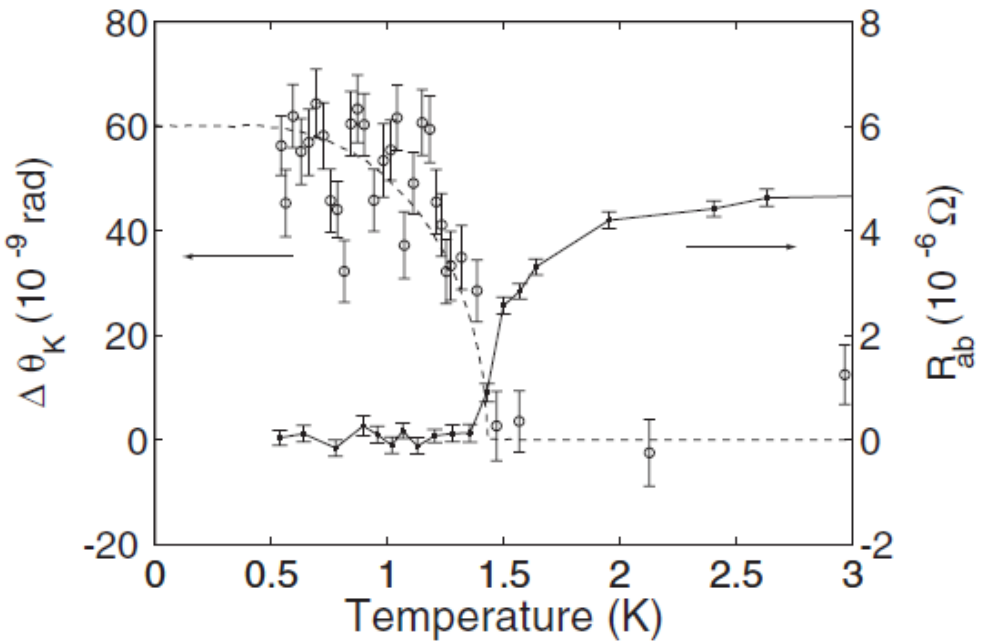
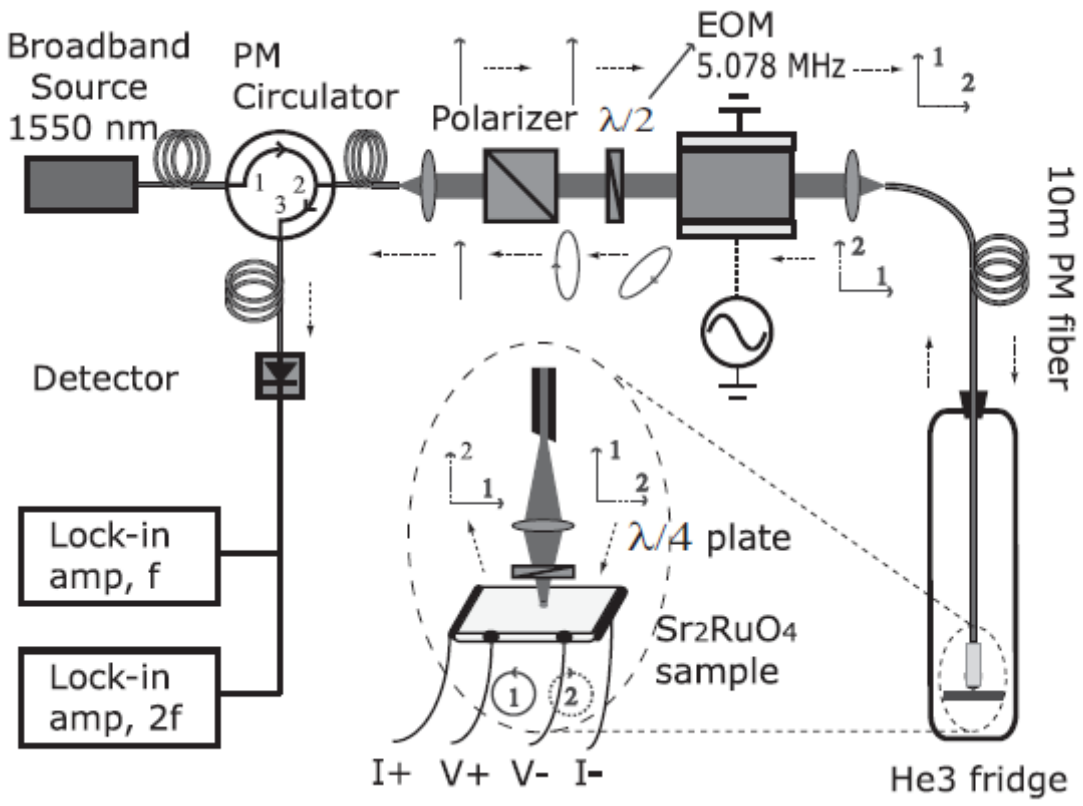
(Received 20 July 2006; published 20 October 2006)

The polar Kerr effect in the spin-triplet superconductor Sr_2RuO_4 was measured with high precision using a Sagnac interferometer with a zero-area Sagnac loop. We observed nonzero Kerr rotations as big as 65 nanorad appearing below T_c in large domains. Our results imply a broken time-reversal symmetry state in the superconducting state of Sr_2RuO_4, similar to ^{3}He-*A*.





Sagnac interferometer for magneto optic measurements

SUPERCONDUCTIVITY

Observation of broken time-reversal symmetry in the heavy-fermion superconductor UPt_3

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W. P. Halperin,[4] A. Kapitulnik[1,2,3,5]

Models of superconductivity in unconventional materials can be experimentally differentiated by the predictions they make for the symmetries of the superconducting order parameter. In the case of the heavy-fermion superconductor UPt_3, a key question is whether its multiple superconducting phases preserve or break time-reversal symmetry (TRS). We tested for asymmetry in the phase shift between left and right circularly polarized light reflected from a single crystal of UPt_3 at normal incidence and found that this so-called polar Kerr effect appears only below the lower of the two zero-field superconducting transition temperatures. Our results provide evidence for broken TRS in the low-temperature superconducting phase of UPt_3, implying a complex two-component order parameter for superconductivity in this system.