Bench testing of new polarimeter with silicon photoelastic modulator for short wavelength FIR laser

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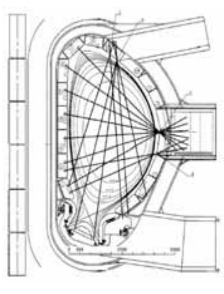
1. Objectives of Research

The current profile (in tokamaks) and the iota profile (in helical systems) are closely related to plasma confinement and the measurements are indispensable to control burning plasmas.

Poloidal polarimeter on ITER



From measurement of **the Faraday rotation α (polarimetry)** and **the electron density**, the current (or the iota) profile can be evaluated.

$$\alpha \propto \lambda^2 \int n_e B_{//} dl$$

The electron density profile can be measured with a interferometer.

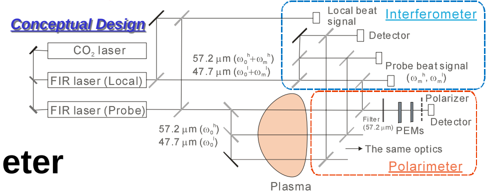
To be free from fringe jump errors, which is caused by beam bending effect (∝$\Delta l/\lambda$), a short wavelength FIR laser is adopted. **A CH_3OD laser beams (57.2 and 47.7 μm)** [1-4] suffer a **small beam bending** and can **compensate a phase error due to mechanical vibrations.**

In this research, polarimeter system with the CH_3OD laser is developed.

- **Polarization Rotation Method** (counter-rotating circularly polarized beams)
  High time resolution and multi-channel with low cost
  Low long time stability
  Instability of beam pointing ⟶ change in interference ⟶ phase noises [5]
- **Polarization Modulation Method** (photoelactic modulator)
  Simple optical system and good compatibility with an interferometer
  Good resolutions and long time stability [6]
  Multi-channel with higher cost than that of PRM

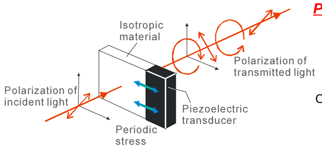
We adopts PMM in the viewpoint of maintenance, compatibility with the interferometer, resolutions and long time phase stability. However, there was no PEM in the FIR region. **Hence we newly developed the PEM and tested the polarimeter with it.**

Conceptual Design



2. Specification of PEM Polarimeter

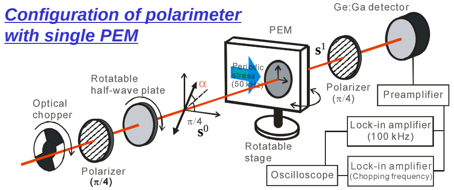
2.1. Principle of PEM Polarimeter



Photoelastic modulator

Mechanical stress to an isotropic solid material
Time-varying birefringence
Optical retardation is modulated
Polarization of transmitted light is modulated

Configuration of polarimeter with single PEM



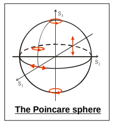
Stokes vector description of the incident beam

$$\mathbf{s}^0 = (\sin 2\alpha,\ \cos 2\alpha,\ 0)$$

Muellar matrix of PEM

$$\mathbf{M}_{\mathrm{PEM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\rho & \sin\rho \\ 0 & -\sin\rho & \cos\rho \end{pmatrix}$$

$$\rho = \rho_0 \sin(\omega_m t)$$



The Poincare sphere

After passing though the PEM [7],

$$\mathbf{s}^1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\rho & \sin\rho \\ 0 & -\sin\rho & \cos\rho \end{pmatrix}\begin{pmatrix} \sin 2\alpha \\ \cos 2\alpha \\ 0 \end{pmatrix} = \begin{pmatrix} \sin 2\alpha \\ \cos\rho\cos 2\alpha \\ -\sin\rho\cos 2\alpha \end{pmatrix}$$

Detected signal I after passing through a polarizer is as follows.

$$\begin{aligned} I &= \frac{I_0}{2}(1+s_2^1) \\ &= \frac{I_0}{2}\{1+\cos 2\alpha\cos(\rho_0 \sin\omega_m t)\} \\ &= \frac{I_0}{2}\left\{1+J_0(\rho_0)+2\cos 2\alpha \sum_{n=1}^{\infty} J_{2n}(\rho_0)\cos(2n\omega_m t)\right\} \\ &= \frac{I_0}{2}\{\underbrace{1+J_0(\rho_0)}_{I\,(\mathrm{DC})}+\underbrace{2J_2(\rho_0)\cos 2\alpha\cos(2\omega_m t)}_{I\,(2\omega_m)}+\cdots\} \end{aligned}$$

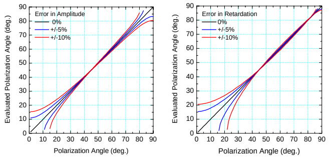
By measuring the amplitudes of DC and $2\omega_m$ components with lock-in amplifiers, α is obtained.

$$\alpha = \frac{1}{2}\cos^{-1}\left(\frac{1}{2AJ_2(\rho_0)-J_0(\rho_0)}\right), \quad A \equiv \frac{I(2\omega_m)}{I(DC)}$$

2.2. Estimation of Error Terms

$$\alpha = \frac{1}{2}\cos^{-1}\left(\frac{1}{2AJ_2(\rho)-J_0(\rho)}\right), \quad A \equiv \frac{I(2\omega_m)}{I(DC)}$$

Effect of errors in the **ratio A** | Effect of errors in the **retardation ρ_0**

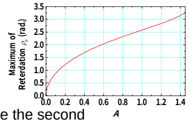


The maximum retardation ρ_0 is necessary to evaluate the polarization angle and should be measured in advance.

- The propagation error from the error in A becomes large when the polarization angle is near 0 and 90 deg.
- The error in the polarization angle derived from the retardation error is significant near a polarization angle of 0 deg.

The retardation depends on

- magnitude of the mechanical stress
- incident angle of a laser beam
- optical constants (dependence on temperature).



In-sitsu calibration of the retardation

1. A half wave plate is set to make α=0 where the second harmonic component is maximum.
2. The measured ratio A corresponds to following formula: $A = \frac{2J_2(\rho_0)}{1+J_0(\rho_0)}$
3. Since this is a one-valued function of ρ_0 in retardation range less than 3.4 rad., ρ_0 can be evaluated.

A slight change in the thickness of the element due to the periodic stress

➡ Modulations the interference and then I_0 at a fundamental and the harmonic frequencies.

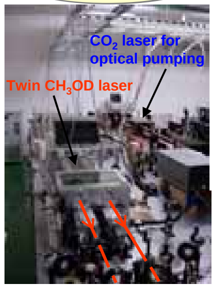
The spurious second harmonic component $I_{spu}(2\omega_m)$ causes error in the polarization angle and the retardation [8].

$$\alpha_{spu} = \frac{1}{2}\cos^{-1}\left(\frac{1}{2A_{spu}J_2(\rho_0)-J_0(\rho_0)}\right) \neq \alpha, \quad A_{spu} \equiv \frac{I(2\omega_m)+I_{spu}(2\omega_m)}{I(DC)}$$

3. Experimental Results

3.1. Short wavelength FIR laser

CH_3OD laser at Chubu University



○ CW CO_2 laser

Line:		9R(8)
Power :		138 W
Flow rate:	$CO_2 + N_2$ (1 : 2)	1.9 l/min.
	He	7.1 l/min.
Pressure:		37.2 hPa
Current:		55 mA
Water temperature:		22 ℃

○ CW FIR laser

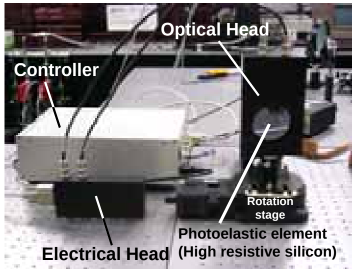
Power : Total	2.4 W	
	57.2 μm	(1.6 W)
	47.7 μm	(0.8 W)
Pressure:	Total	60 Pa
	CH_3OD	44 Pa
	He	16 Pa
Wall temperature:		-6.4 ℃

- A phase error due to mechanical vibrations (∝$\Delta l / \lambda$) is significant in the case of a short wavelength interferometer.

➡ Vibration compensation with a shorter wavelength interferometer (usually He-Ne laser, CW YAG laser, etc.)
However, complex system, uncompensated vibrations because of incompleteness of the beam paths (necessity of careful beam alignment)

- Intrinsic and simultaneous laser oscillation of wavelengths of 57.2 and 47.7 μm overcomes the problem of the short wavelength interferometer.

3.2. Development of Silicon PEM



Produced by HINDS Instruments, Ltd.

New development of photoelastic modulator for FIR laser

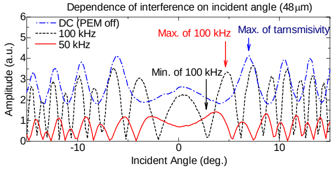
Photoelastic element: High resistive silicon

- About 10 kΩ・cm
- Optically isotropic material
- Relatively low absorption in a pure silicon (without doping impurities)

Effective aperture:		ϕ60 mm
Drive frequency:		50 kHz
The maximum retardation (measured):		
	57.2 μm	2.7 rad.
	47.7 μm	3.0 rad.
Transmissivity (normal incidence):		
	57.2 μm	50 %
	47.7 μm	25 %

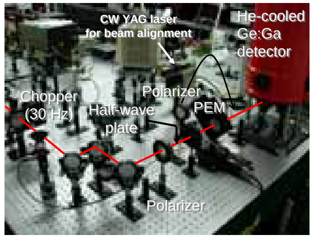
- There was no PEM in the FIR region.
- Refractive index of the high resistive silicon is expected so large 3.4 that the reflection at the surface is large ($R = \{(n_{Si}-1)/(n_{Si}+1)\}^2$). But an anti-reflection (AR) coating has not been done yet.
- In order to minimize the spurious second harmonic components, the PEM is tilted.

Dependence of interference on incident angle (48μm)



- Even if the configuration with tilted PEM, transmissivity is 50 and 30 % for 57.2 and 47.7 μm, respectively. This is because the incident angles where the total intensity and the spurious second harmonic component take external values are different.

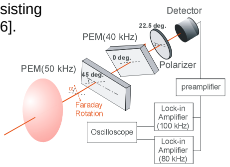
3.3. Test of Si PEM polarimeter



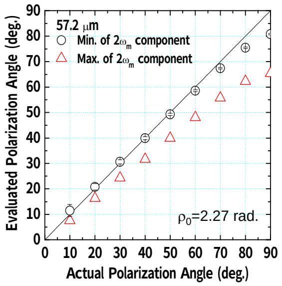
- Since visible light cannot pass though silicon, CW YAG laser (1.06 μm) is used for beam alignment. It can be visualized with an IR sensor card and an Infrared viewer.
- A Detector is a liquid helium cooled gallium-doped germanium photoconductor.
- One wavelength is selected with a polarizer and tested separately; the polarization of two wavelength is orthogonal.
- The Faraday rotation is simulated with a half wave plate made from crystal quartz.

Long time constant (300 ms) is due to the low frequency of beam chopping to measure the DC component. The polarization angle can be evaluated from a couple of second harmonic components without the DC component by consisting of **dual PEM system** [6].

$$\alpha = \frac{1}{2}\tan^{-1}\left(\frac{I(2\omega_{m1})}{I(2\omega_{m2})}\right)$$



We have a plane to make the second Si PEM with a drive frequency of 40 kHz.



Measurement test of the polarization angle

Error bars show errors in the polarization angle derived from electrical noises (±3 mV in the case of a time constant of 300 ms of lock-in amplifiers) in measured amplitudes of detected signals. Error bar changes according to the polarization angle.

An evaluated polarization angle shows good agreement with an actual polarization angle (estimated from the rotation angle of the half-wave plate) in a polarization angle is smaller than 70 deg. when the spurious second harmonic component due to the modulated interference is minimized (○).

The large deviation when the spurious component is maximized (△).

There is the deviation in a polarization angle larger than 70 deg. even when the spurious component is minimized. The reason is speculated as follows. The reflectivity of s- and p- polarization components is slightly different. Hence, the spurious component might increases when the polarization rotates.

We can evaluated actual polarization angle from non-linear relationship between evaluated and actual polarization angle by a calibration experiment. However, the cause should be eliminated because slight change in the incident beam make the calibration formula different.

Plans of AR-coating is going.

However, there are only a few applications of the AR coating for FIR light so far ! Good coating material (low absorption, strong adhesion, technology for thick coating width, weak stress to silicon, etc.) should be looked for.

Parylene (plastic) [9] d_{AR} = 8.8 μm (n_{AR}=1.62)
thick width is O.K., but no data of n_{AR} and absorption for 57 μm, weak adhesion?

SiO_2 [10] d_{AR} = 6.8 μm (n_{AR}=2.10)
strong adhesion, but the stress is so strong that it may cause photoelastic effect by itself.

➡ **Reflectivity expected to be reduced to about 2% from 30% with these coatings.**

4. Summary

- The Si PEM has been newly developed for a polarimeter using a short wavelength FIR laser, which is suitable for large fusion devices.
- The polarimeter with the new Si PEM can measure the polarization angle successfully.
- The measurement error of amplitude of a detector signal and the retardation results in non-linear errors in evaluated polarization angle.
- Since a multi-reflection in the photoelastic element also causes the deviation from an actual polarization angle, it should be suppressed by tilting the PEM or an AR-coating.

Reference

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