Development of a two-color interferometer using short-wavelength FIR lasers for plasma diagnostics

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Object of this visit

- To study the operational characteristics (remote control, vibration isolation, etc.) of the FIR laser interferometer /polarimeter on NSTX.
- Implement new technology to the two-color measurements system using 50 μm FIR lasers.

LHD

- 13ch 119-μm laser interferometer (routinely use)
- 50 μm laser two color int. or int./pol. (under development)

NSTX

- 4ch (7ch) 119- μm laser interferometer/polarimeter (routinely use)

ITER

- Multi-channel two-color laser interferometer/polarimeter using 50 μm lasers

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2. Laser

   ・Development of high power 48-and 57-μm FIR lasers

3. Optical elements (BS, Window)

   ・Measurement of optical constants (*n*, *a*) of a CVD-diamond and silicon

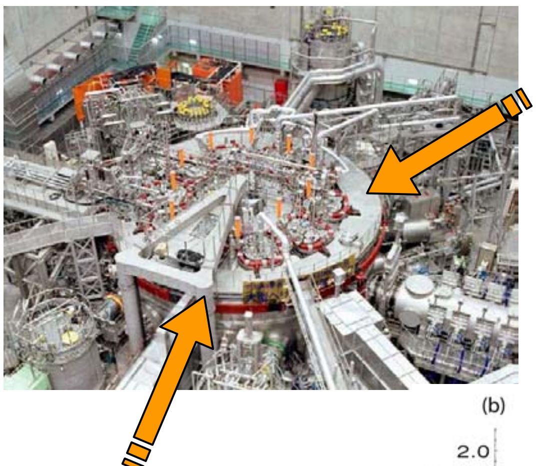
   ・Calculation of transmissivity of a metal-mesh

4. Summary

Introduction

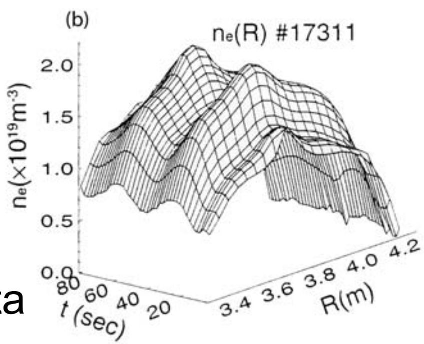
- **Electron density profile in LHD (NIFS)**

  ⇒119-μm laser interferometer (routinely use)



Large Helical Device

Interferometer frame



Example of measurements data

- **High density operation**
  1. Plasma refraction effect
  2. Mechanical vibration effect

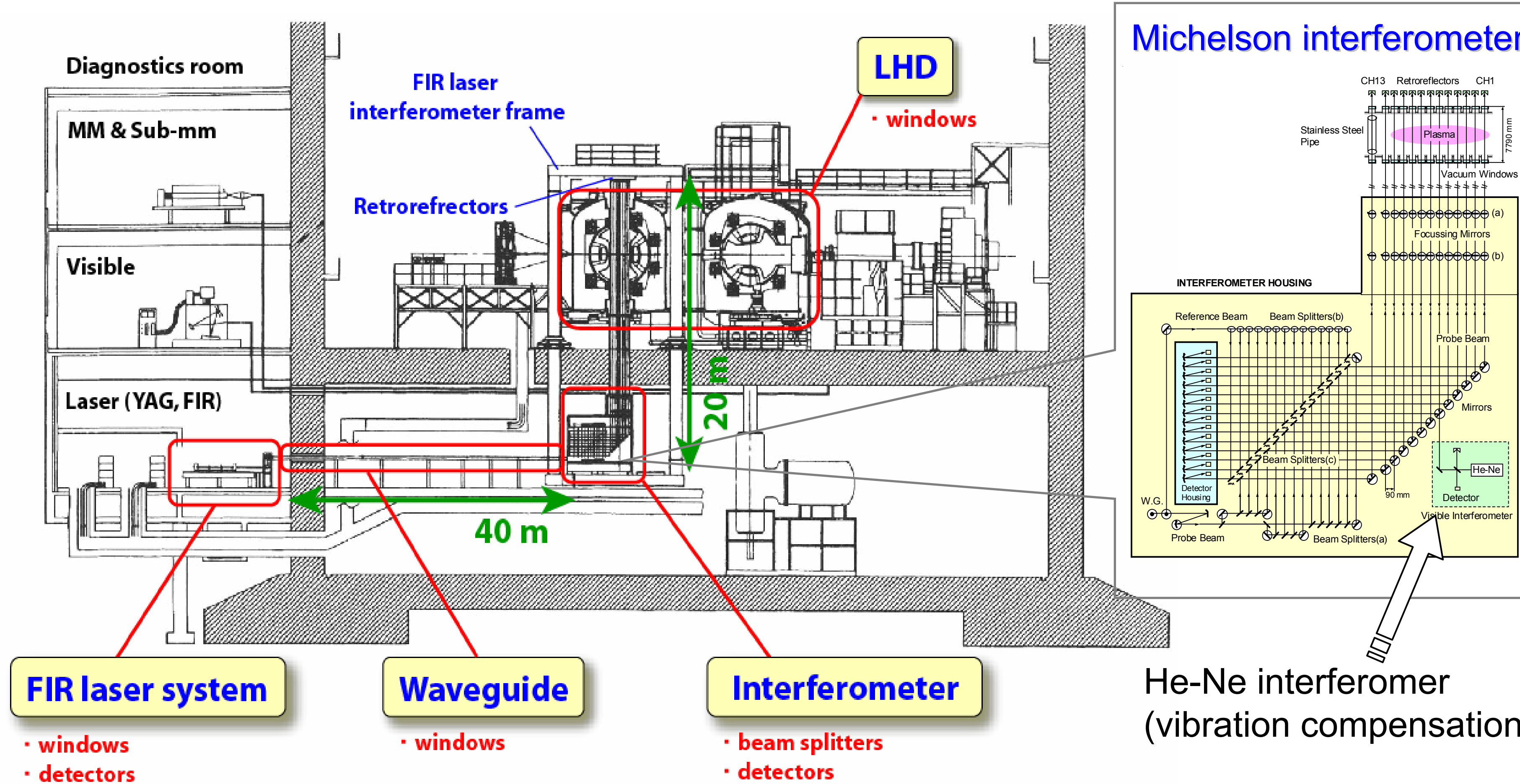
- **Optimum wavelength**

  ⇒ **～50 μm** (ITER also)

  Undeveloped region

- **Development of the short-wavelength FIR laser interferometer**
  1. Laser,
  2. Optical elements (Win, BS),
  3. Detector,
  4. Transmission guide, etc.

13-ch FIR laser interferometer

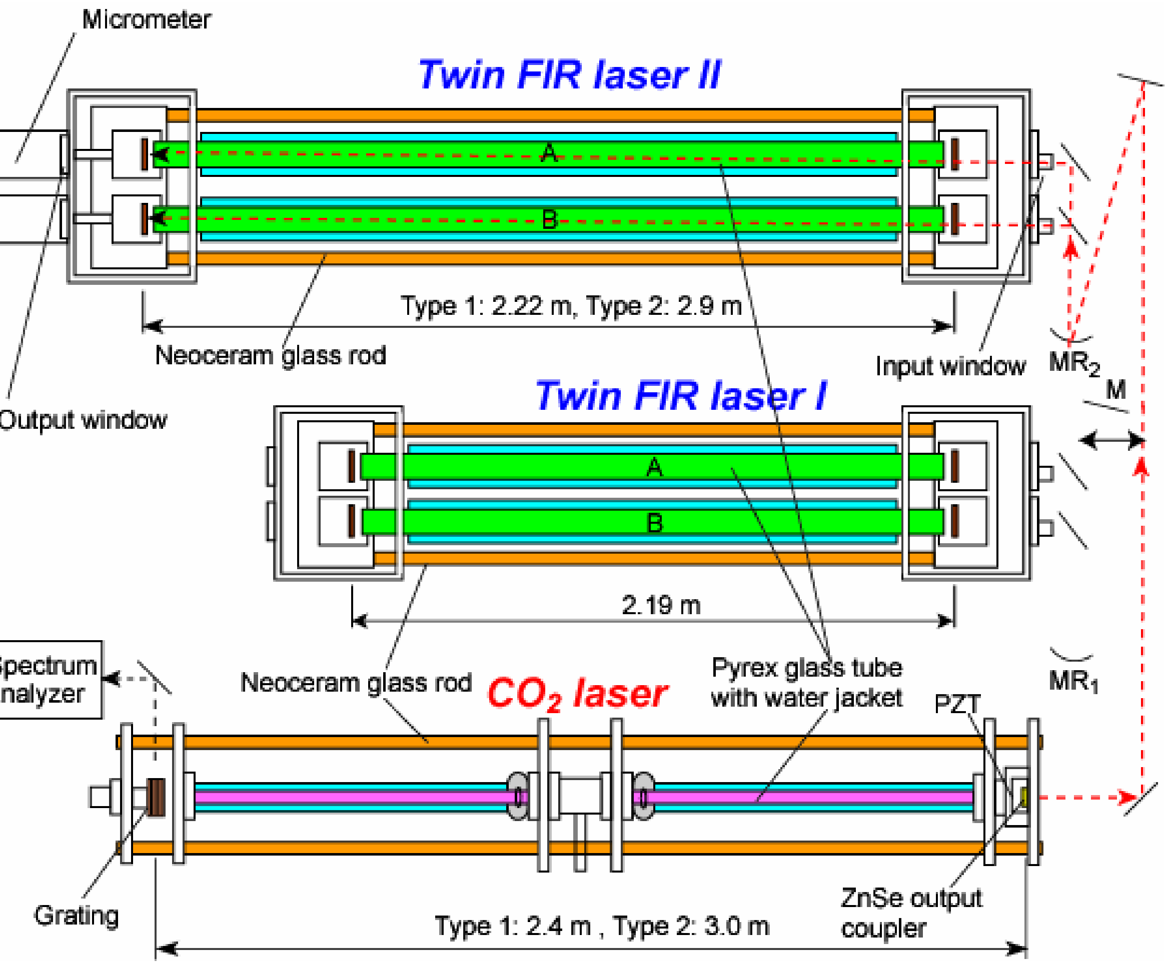


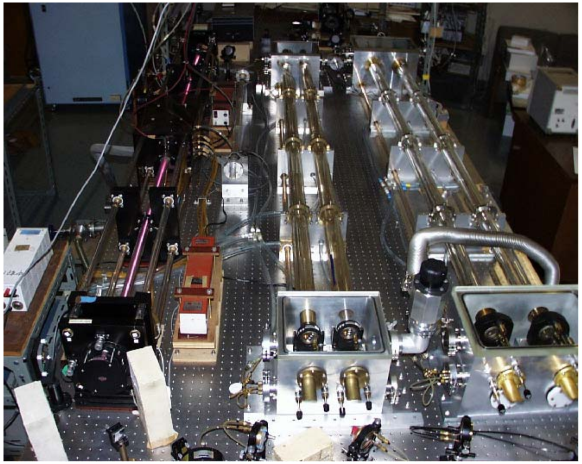
- **Laser**
  119 μm ⇒ 50 μm

- **Optical elements**
  X-tal qu ⇒ Si ?
  Diamond ?
  Mesh ?

- **Detector**
  GaAs SBD ⇒ Ga:As SBD ?
  Ge:Ga photocon.?

CO_2 laser pumped FIR laser system (Chubu University)





■CO_2 laser power：cw **250 W** @10P(20)

■FIR molecules：13 kinds（CH_3OH, NH_3, HCOOH, etc.）

■Wavelenght regions：**40 - 500 μm**

■FIR laser lines：**80 lines**

Short-wavelength FIR laser lines

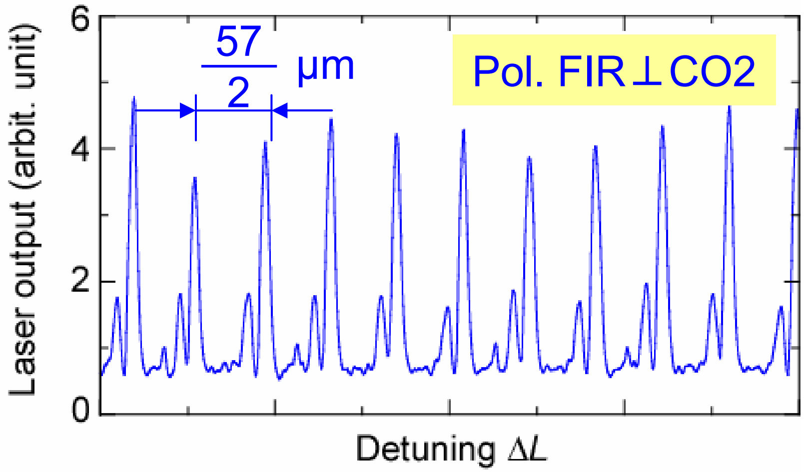
(λ = 40～100 μm)

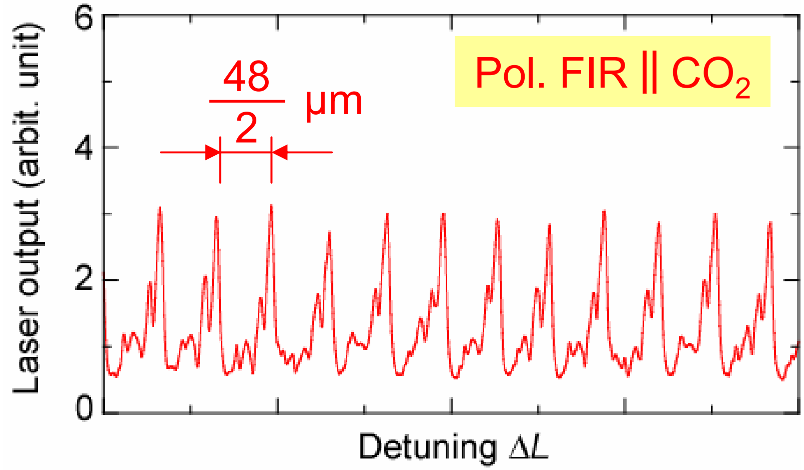
Pump CO_2 laser			FIR laser								
Line	Length (m)	Power (W)	Molecule	Wavelength (μm)	Pol.	Pressure (Pa)	He (Pa)	Power (mW)	Length (m)	Tube dia. (mm)	Output mirror*
9R(18)	3.0	129	CH_3OH	61.6	⊥	36	–	9.5	2.92	25	Si hybrid(14)
9R(10)	2.4	83	CH_3OH	96.5	∥	93	–	68	2.22	22	Si hybrid(8)
9R(8)	2.4	65	CH_3OH	77.3	∥	101	–	1.5	2.22	22	Si hybrid(8)
9P(34)	2.4	75	CH_3OH	70.5	⊥	27	–	65	2.19	34	Si hybrid(8)
10R(16)	3.0	123	CH_3OH	63.0	∥	60	–	54	2.92	25	Si hybrid(14)
9R(34)	2.4	63	CD_3OH	52.9	⊥	47	–	10	2.19	34	Si hybrid(8)
9R(28)	2.4	81	CD_3OH	55.6	⊥	40	–	4	2.19	34	Si hybrid(8)
	2.4	78	CD_3OH	42.6	∥	33	–	4	2.19	34	Si hybrid(8)
10R(18)	2.4	89	CD_3OH	41.4	⊥	24	–	13	2.19	34	Si hybrid(8)
	2.4	107	CD_3OH	43.7	∥	40	–	6	2.19	34	Si hybrid(8)
10R(16)	3.0	113	CD_3OH	81.6	∥	47	–	25	2.92	25	Si hybrid(14)
	2.4	99	CD_3OH	86.4	⊥	40	–	–	2.19	34	Si hybrid(8)
9R(8)	3.0	**138**	**CH_3OD**	**57.2**	⊥	60	16	**1.6W**	2.92	25	Si hybrid(14)
	3.0	**138**	**CH_3OD**	**47.6**	∥	60	16	**0.8W**	2.92	25	Si hybrid(14)
9P(30)	2.4	95	CH_2DOH	44	∥	17	–	6	2.19	25	Si hybrid(8)
10P(46)	2.4	43	CH_2DOH	49.1	⊥	27	–	17	2.19	25	Si hybrid(8)
9R(30)	2.4	65	NH_3	67.2	∥	55	–	97	2.22	22	Si hybrid(8)
10R(14)	2.4	76	NH_3	77.3	∥	53	–	–	2.22	22	Si hybrid(8)

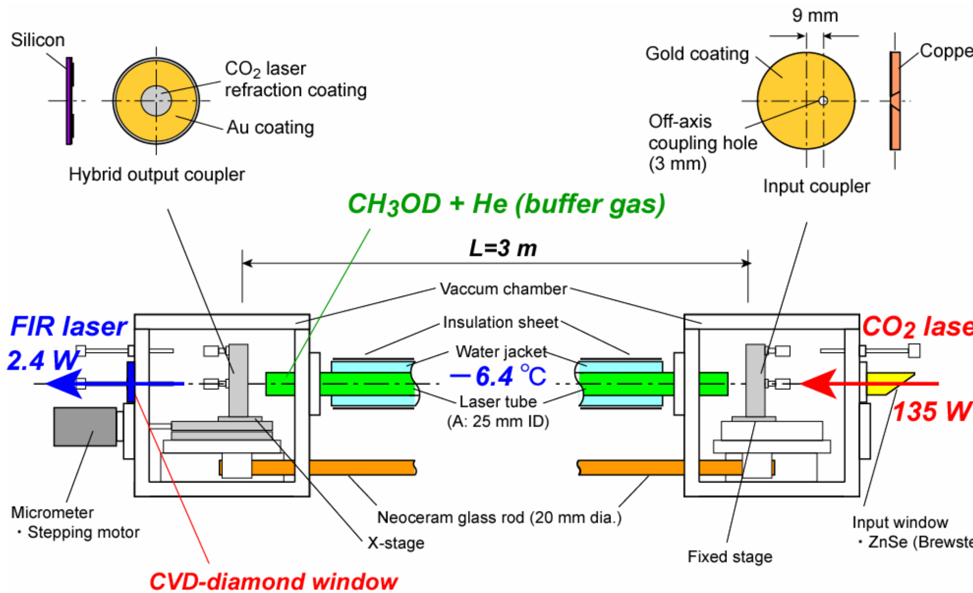
* Diameter of coupling hole (mm)

High-power 48- and 57-μm CH_3OD lasers pumped by 9R(8) CO_2 laser

Detuning curves



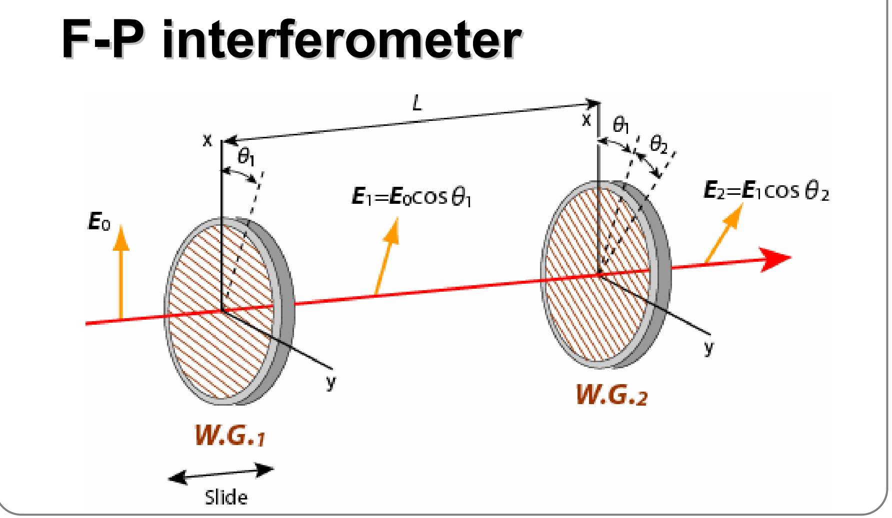


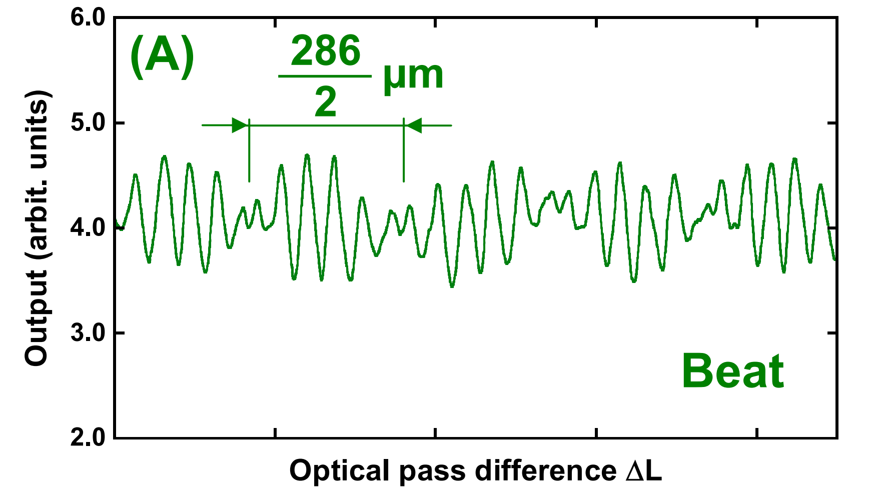


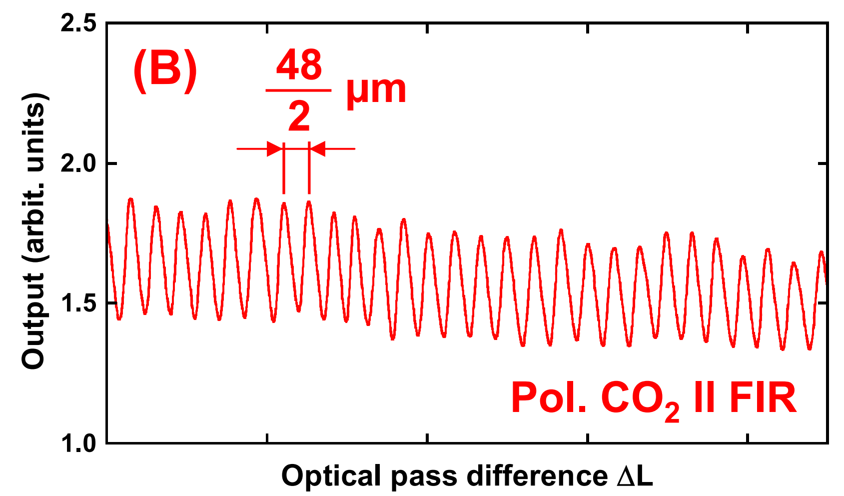
Power meter : H310(Detector model AC500H), Scientech. Inc

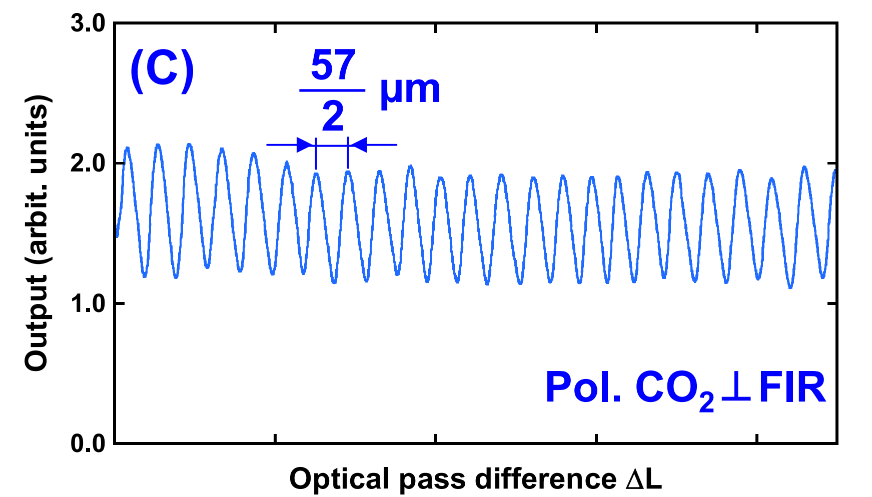
- Output power
  - Total : **2.4 W**
  - 57-μm : (1.6 W)
  - 48-μm : (0.8 W)
- Output stability (free running)
  - 57-μm: ±1 %/30min
  - 48-μm: ±2 %/30min

Simultaneous oscillation of 48- and 57 μm lasers

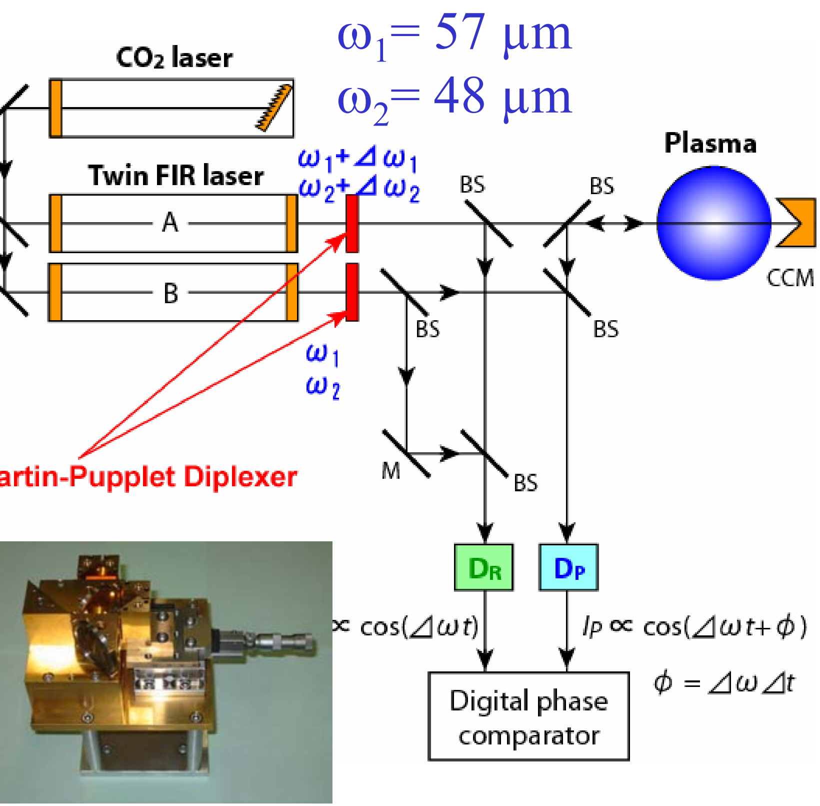








New two color FIR laser interferometer



The diplexer is used to obtain the co-polarization.

- 48- and 57-μm lasers are optimum probe beams for LHD and ITER.
- Both lasers oscillate simultaneousl
- BS and windows can be optimized at both lasers by choosing the etalon's thickness.
- An additional laser is not needed to compensate the fringe shift due to mechanical vibration.
- Same optical pass.
- One detector detects the beat signa of both lasers simultaneously, and each interference signal can be electrically separated.

Observation of new FIR laser lines

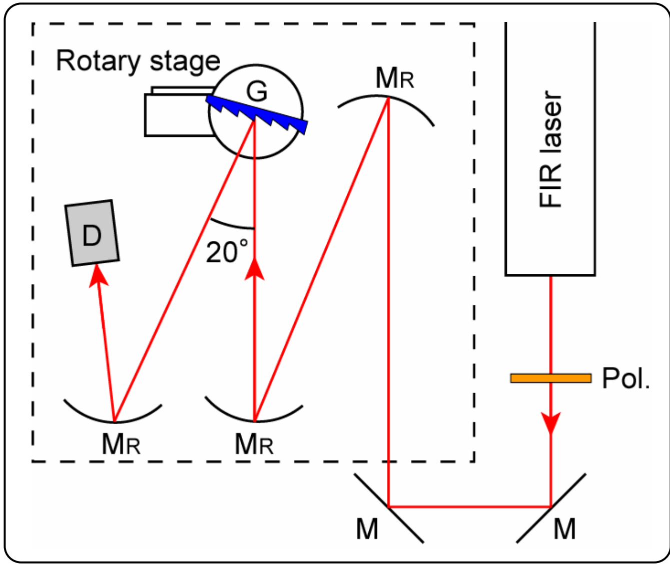
CH_3OD lasers pumped by $9R(8)CO_2$ laser

Wavelength (μm)	Frequency (MHz)	Rel. Pol.	Operation
47.65	-	‖	cw
■ 54.2	-	‖	cw
57.1511	5245612.9	⊥	cw, pulsed
■ 85.4	-	‖	cw
289.6	-	‖	cw
295	1016897.2	‖ , ⊥	cw
306	980591.6	‖ , ⊥	cw
825.0	-	-	cw

These lasers were not observed

■ New laser line

Czerny-Turner mount

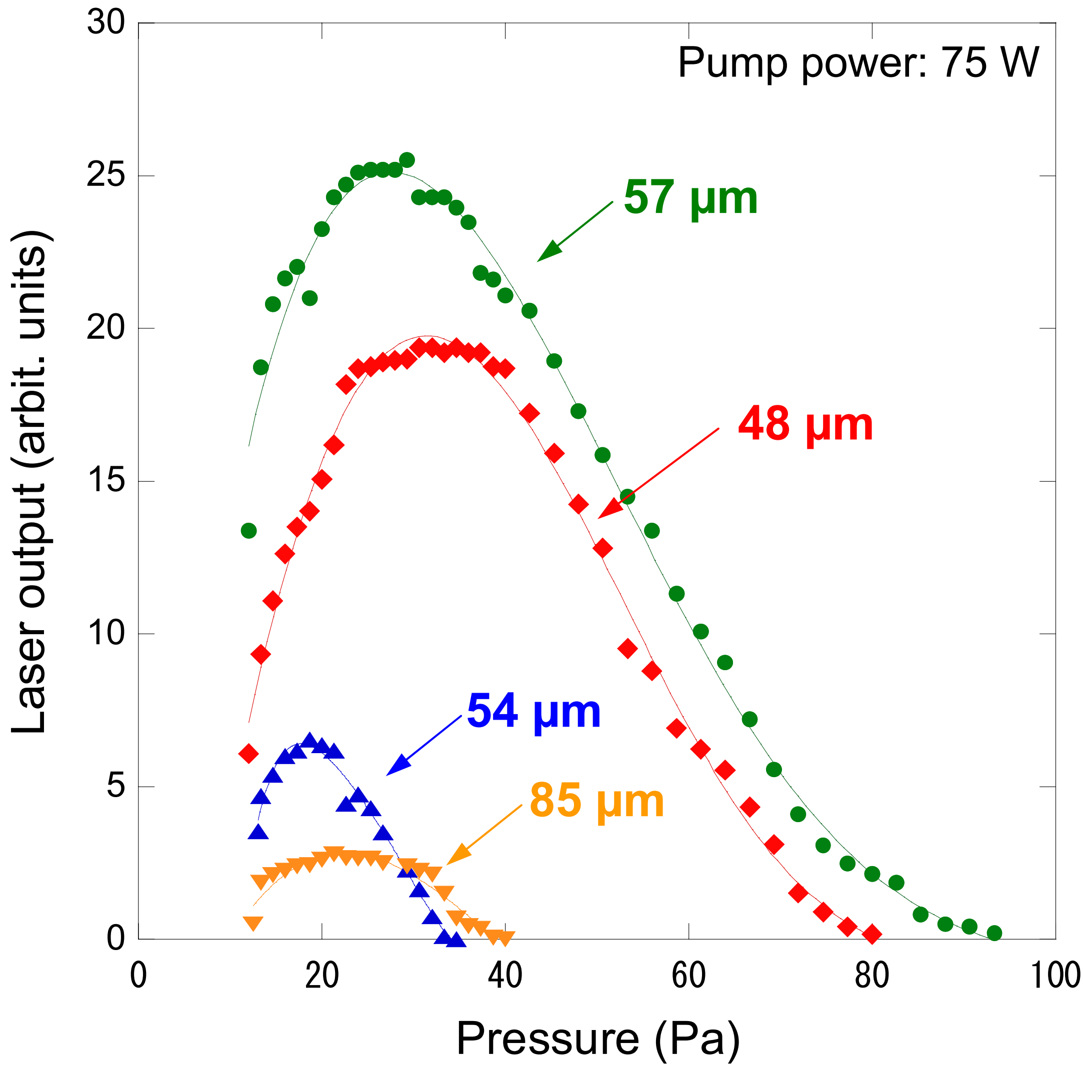


Diffraction grating

Spacing: 220 μm

Blaze angle; 26°

Pressure dependence of CH_3OD lasers pumped by 9R(8) CO_2 laser



- New lasers are weaker than 48- and 57-μm lasers.
- These lasers can be separated by the pressure dependence and the cavity tuning.

New FIR laser for 48- and 57 μm lasers (Chubu University)

◆ Old
L_{FIR} = 3 m
L_{co2} = 2.4 m

◆ New laser
(under construction)
L_{FIR} = 4 m
L_{co2} = 4 m

- Single mode
- High power
- High stability (feedback control)

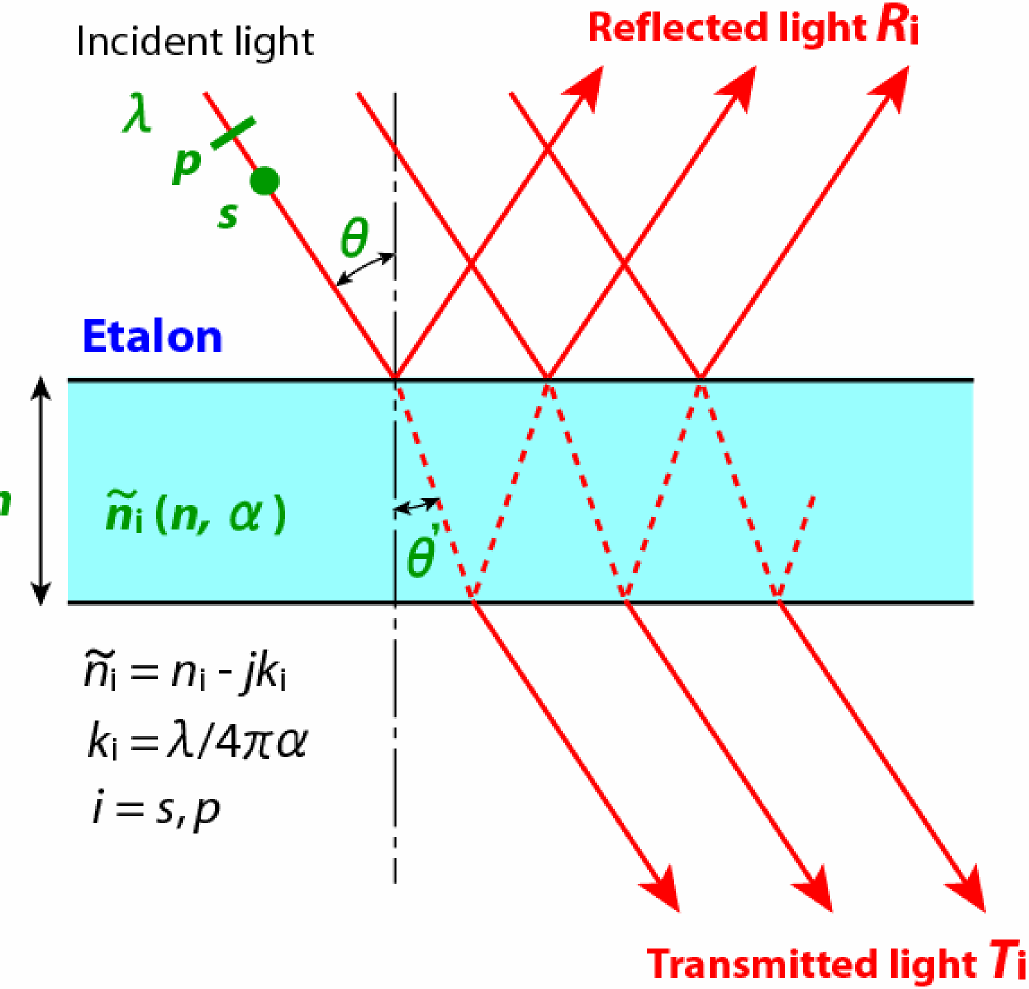
Choice of the optical materials for windows and BS

Properties	CVD-diamond	Silicon	Crystal quartz	Wire-grid/ Metal-mesh
Small absorption	○	○	× $\lambda < 100\ \mu m$	○
Transparency (visible)	○	×	○	△
Mechanical strength	○	○	○	△
Other	Expensive			BS only
	To design windows and BS within ± 2 % in precision of T/R, the refractive index of 5 figures and absorption coefficient of 2 figures are necessary.			

- The reliable optical constants for short-wavelength FIR laser wavelength are unknown.

- The optical constants have been precisely measured by using short-wavelength FIR lasers.
- Design of the common window and BS for 48- and 57-μm lasers

Reflectivity and transmissivity by multiple reflection of an etalon



$$R_i = \frac{r_i(1 + A_i^2 - 2A_i \cos\delta_i)}{1 + A_i^2 r_i^2 - 2A_i r_i \cos\delta_i}$$

$$T_i = \frac{A_i t_i^2}{1 + A_i^2 r_i^2 - 2A_i r_i \cos\delta_i}$$

where

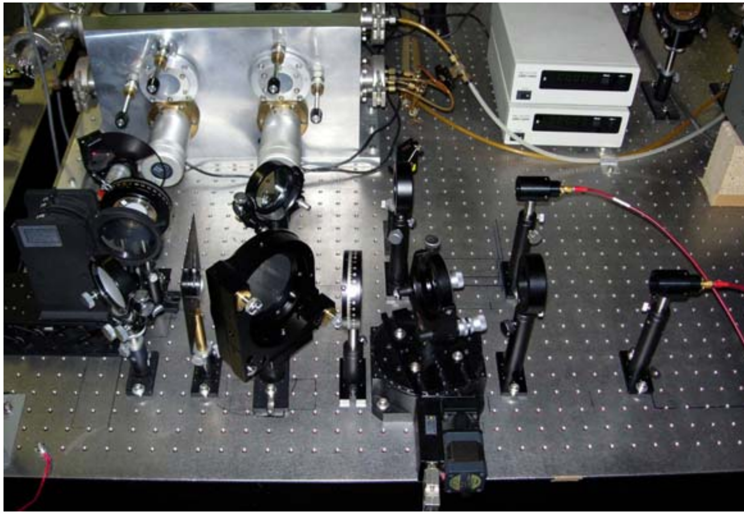
$$A_i = \exp\left(-\alpha_i n_i h (n_i^2 - \sin^2\theta)^{-\frac{1}{2}}\right)$$

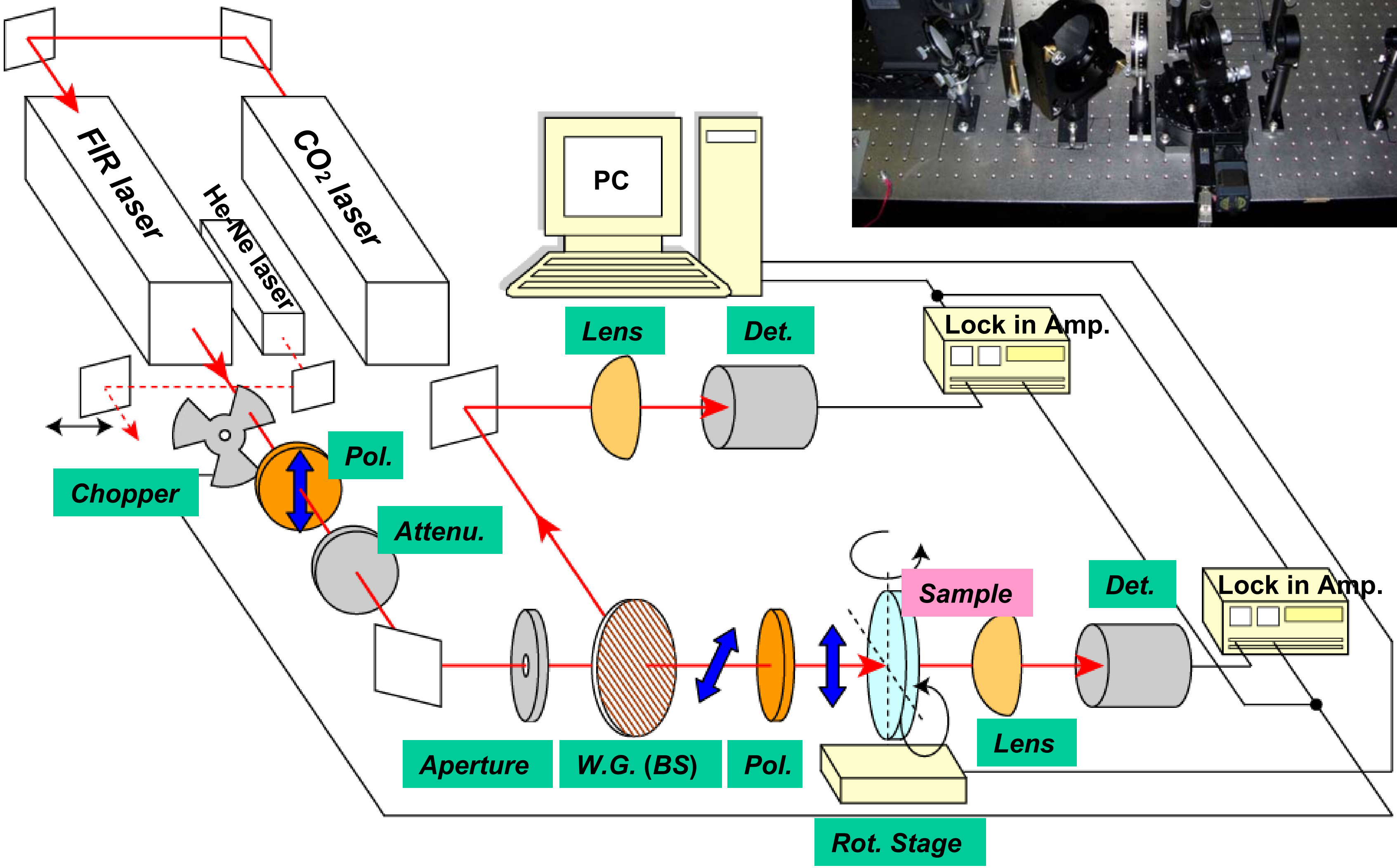
$$\delta_i = \frac{4\pi h}{\lambda}(n_i^2 - \sin^2\theta)^{-\frac{1}{2}}$$

r_i, t_i are given by Frenel's formulae

$\lambda, h, \theta, T \Rightarrow n, \alpha$

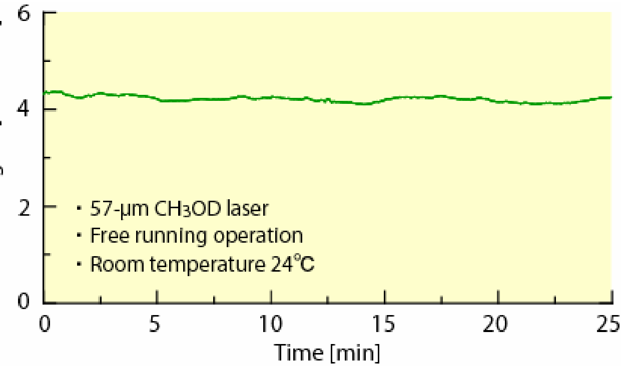
Experimental setup



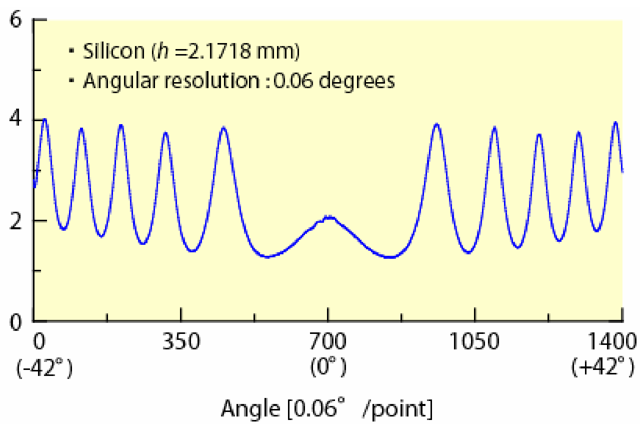


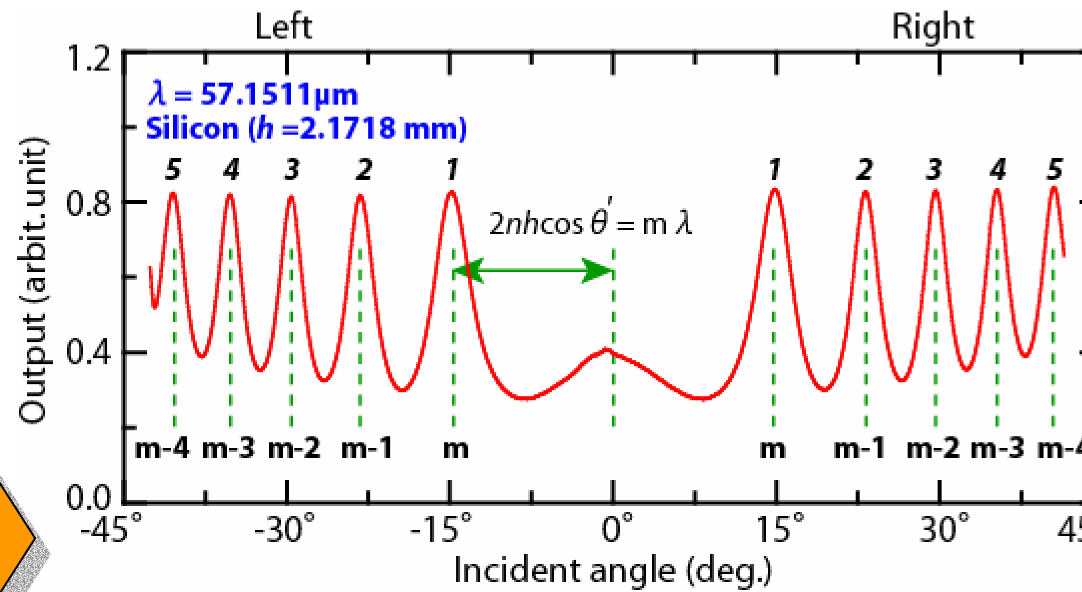
Example of the measurement data and calculation of the refractive index

Reference



Probe





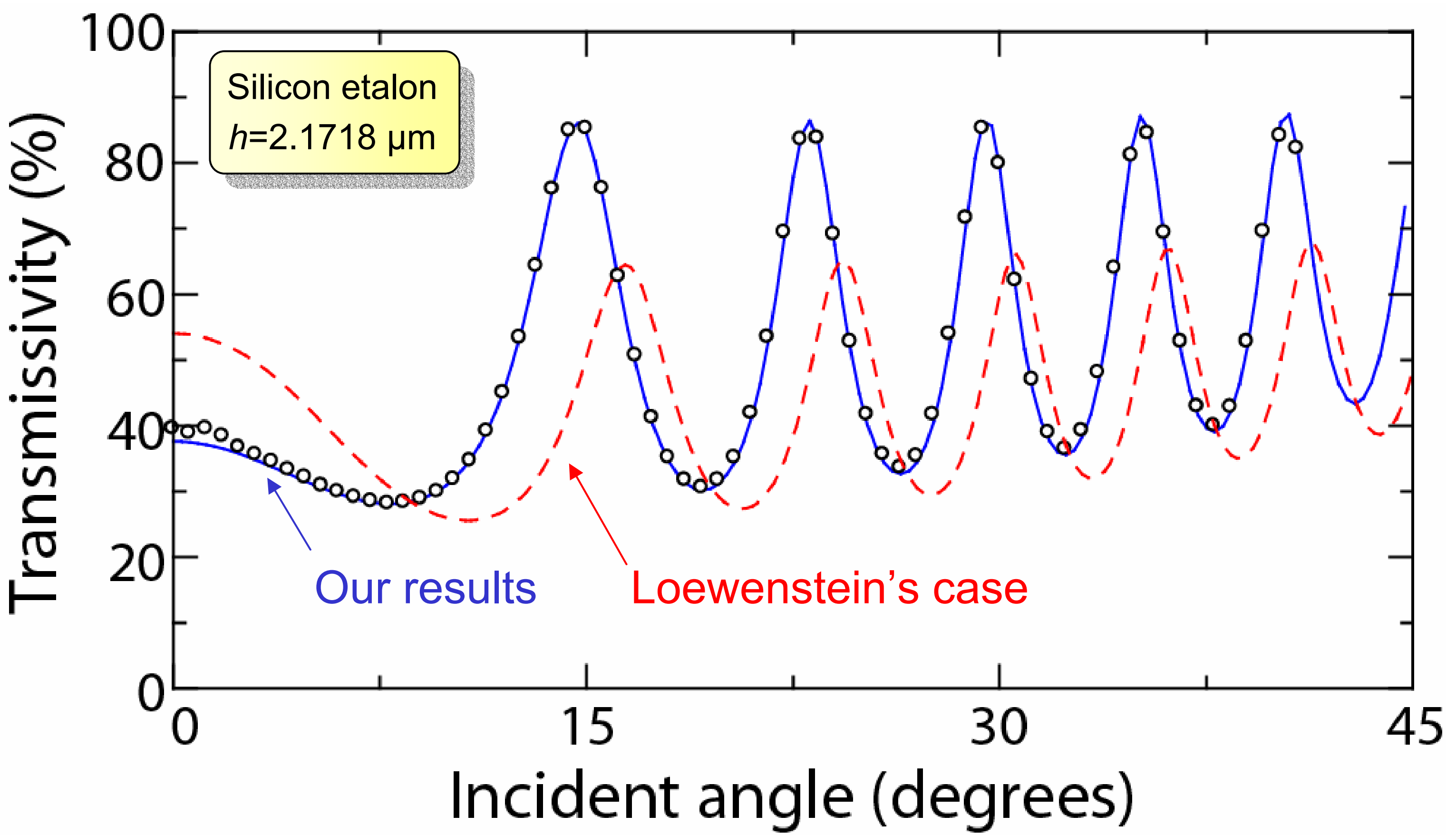
Peak No.	Incident angle* [°]	Refractive index n m=258	m=259	m=260
1	14.66	3.40407	3.41719	3.43032
2	23.07	3.40412	3.41719	3.43026
3	29.50	3.40414	3.41716	3.43018
4	35.16	3.40423	3.41720	3.43017
5	40.39	3.40425	3.41717	3.43009
	Average	3.40416	3.41718	3.4302
	Standard deviation	0.00007	0.00001	0.00008

* (Right−Left)/2

Optical constants (n, α, T)

Material	Refractive index		Absorption coefficient (/cm)		Transmittance (%)	
	57 μm	48 μm	57 μm	48 μm	57 μm	48 μm
CVD-diamond h=1.023 mm	2.383(1) ±0.002	2.383(0) ±0.002	0.19 ±0.05	0.25 ±0.05	98	97
Crystal quartz Extraordinary ray, h=1.5845 mm	2.2306 ±0.0002	2.260(4) ±0.001	2.9 ±0.1	4.9 ±0.2	55	38
Silicon h=2.1718 mm, R=2.8 kΩcm	3.4172 ±0.0005	3.417 ±0.001	0.39 ±0.05	0.57 ±0.05	86	80
Polyethylene h=0.9 mm	——	——	——	——	86	79
Mylar h=0.1 mm	——	——	——	——	50	47
Wire grid a=5 μm, d=12.5 μm	——	——	——	——	93(⊥)	89(⊥)

Transmissivity as a function of the incident angle for 57.1511 μm light



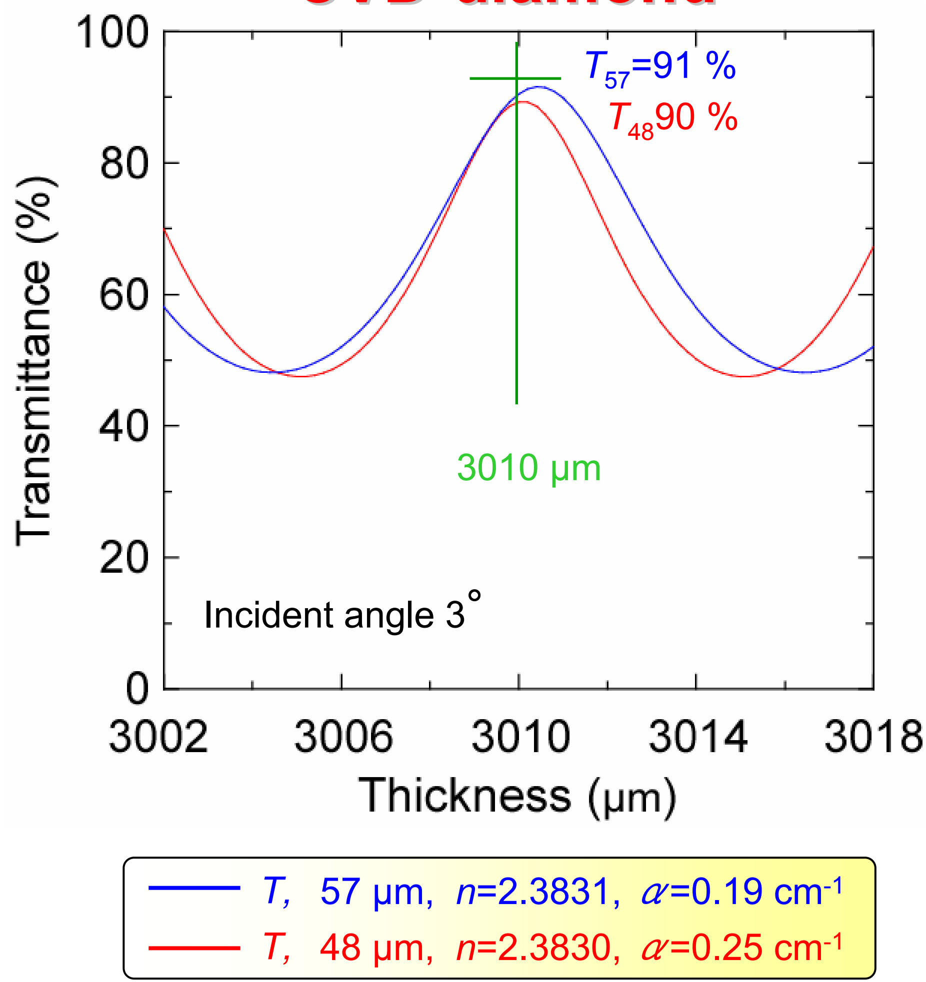
○ Experimental

Calculated (n=3.4172, α=0.39 cm^{-1}) by our results

Calculated (n=3.4195, α=1.2 cm^{-1}) by Loewenstein's case

Design of a common use window for 48- and 57-μm lasers

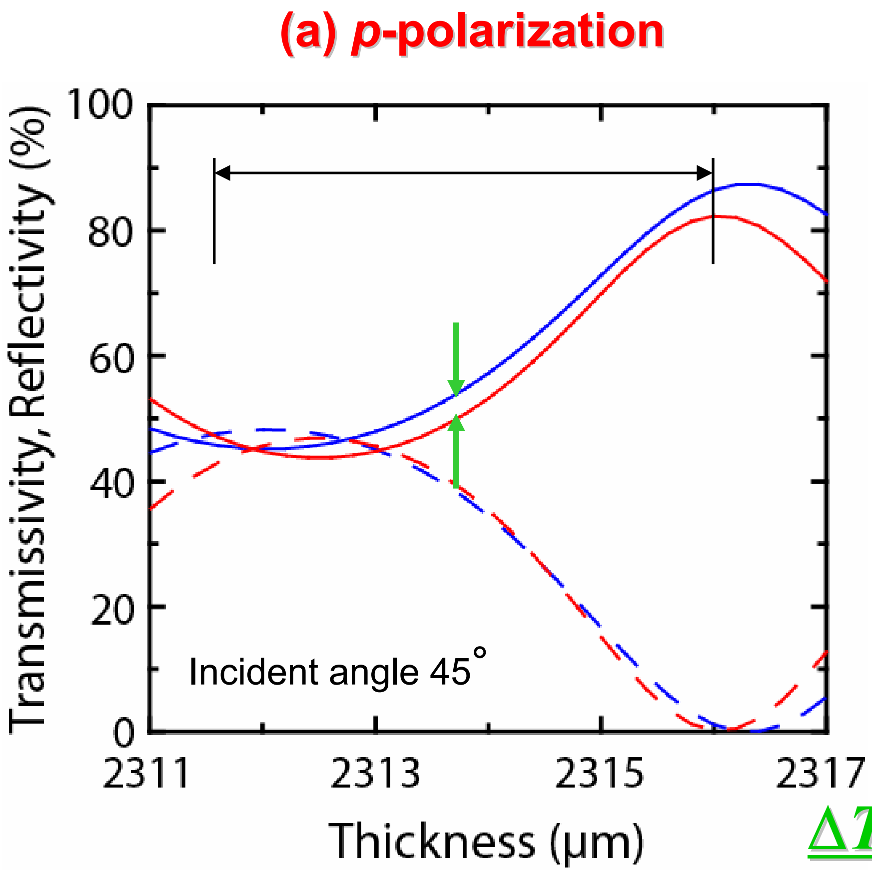
CVD-diamond

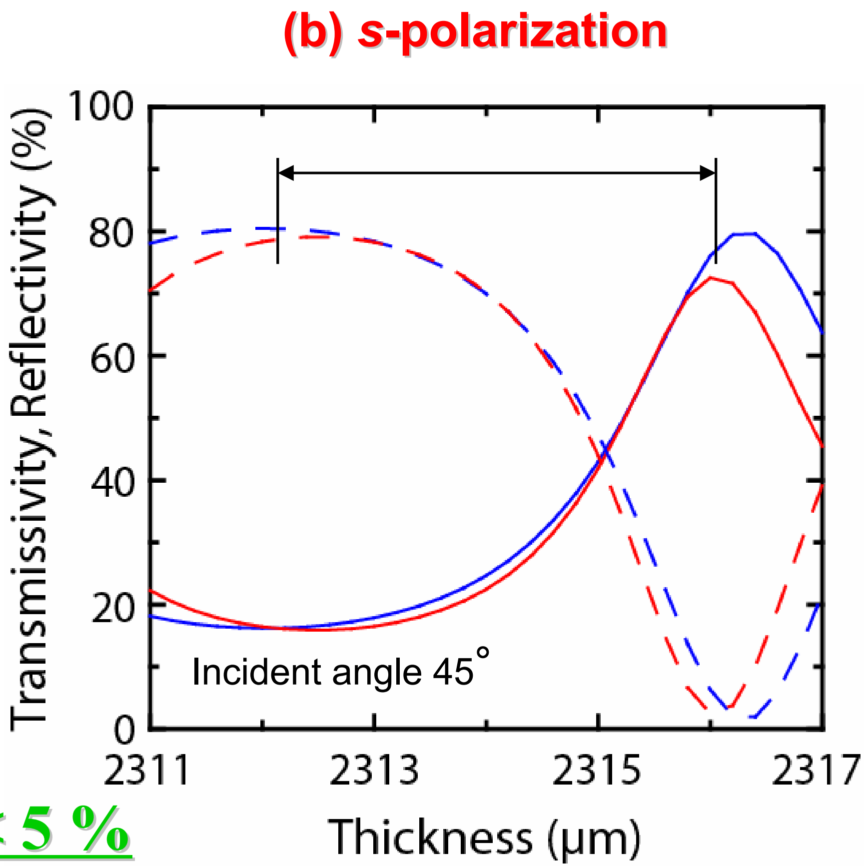


Window design (thickness～3mm)

- **CVD-diamond**
  T_{4857} = 90 %
- **Silicon**
  T_{4857} = 75 %
- **Crystal quartz**
  T_{4857} = 20%

Design of a two color beam splitter using a silicon etalon for 48- and 57-μm laser



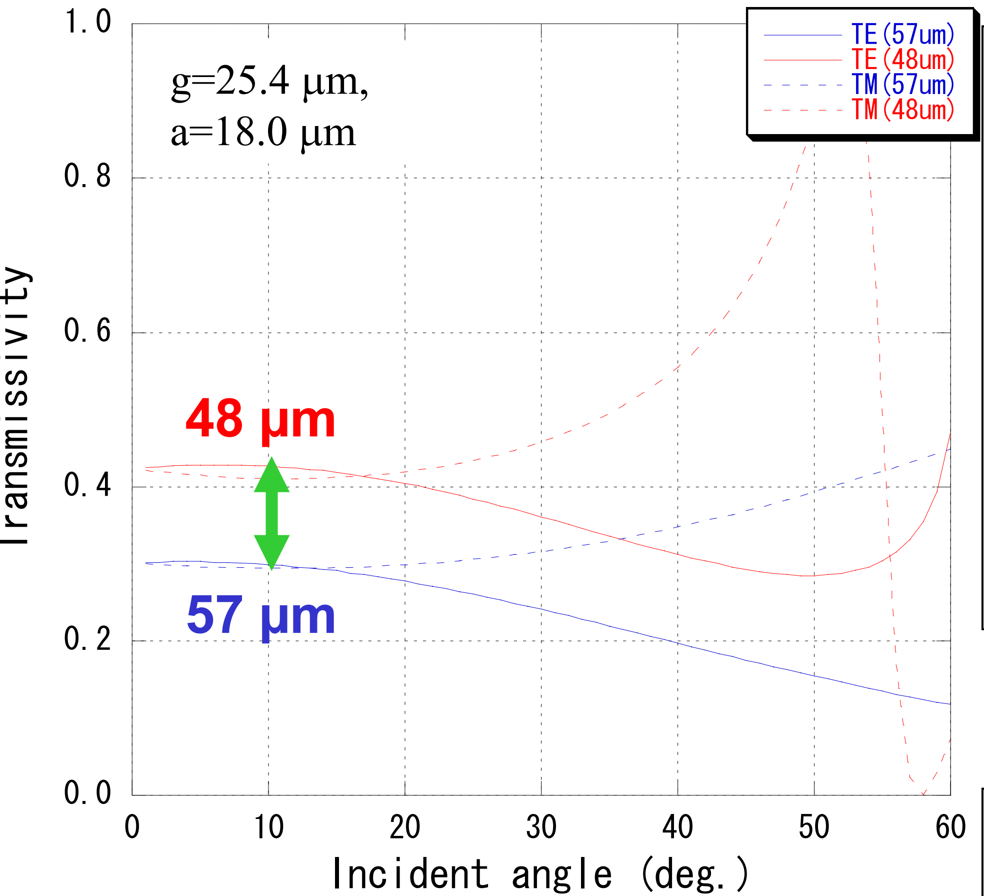


$\Delta T < 5$ %

—— T, - - - - R,	57 μm, n=3.4172, α=0.39 cm^{-1}
—— T, - - - - R,	48 μm, n=3.417<u>2</u>*, α=0.57 cm^{-1}

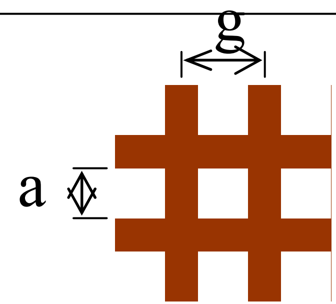
*Assumed data

Calculation of the transmissivity of metal-mesh for 48- and 57-μm lasers



*Lumped circuit model of meshes (Appl. Opt. 23, 4228, 1984) is used in this calculation.

Metal-mesh



- Small absorption
- T/R can be optimized by choosing the grid and aperture size.
- Metal meshes are used as the BS in FIReTIP (λ=119 μm) on NSTX.

$\Delta T \sim 10$ %

- It is difficult to obtain BS with the same ratio (T/R) for 48 and 57-μm lasers.

Summary

- For high density operation of LHD and future large plasma devices such as ITER, a new two color FIR laser interferometer is under development.
- Powerful 48- and 57-μm lasers have been obtained.
- Precise optical constants of CVD-diamond and silicon have been measured to design the window and the BS for both lasers.
- Common use windows (CVD-diamond) and BS (silicon) for both lasers have been designed.
- Although metal mesh is small absorption, it is difficult to obtained BS with same ratio (T/R) for both lasers.