Development of Short-Wavelength Far-Infrared Lasers and Optical Elements

Chubu University[1)]　National Institute for Fusion Science(NIFS)[2)]

K. Nakayama[1)], M. Tomimoto[1)], and S. Okajima[1)],

K. Kawahata[2)], K. Tanaka[2)], T. Tokuzawa[2)], T. Akiyama[2)], and Y. Ito[2)]

Introduction

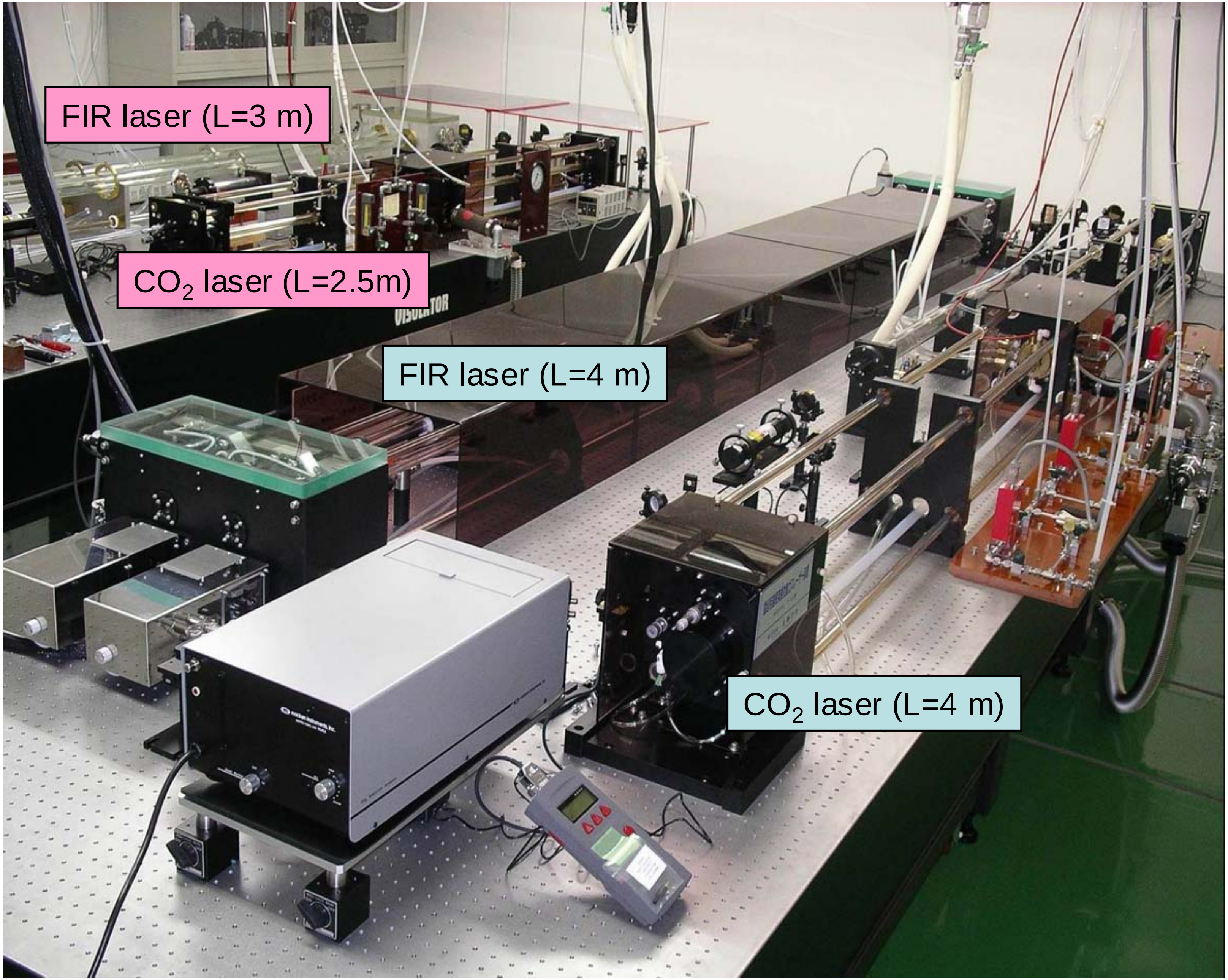
Far-infrared (FIR) lasers have been utilized as optical sources to measure an electron density of fusion plasmas. Powerful 48- and 57-µm CH_3OD lasers pumped by a 9R(8) CO_2 laser have been developed to establish a new two-color FIR laser interferometer system for high density operation of the LHD and large volume plasma devices such as ITER.

To design the collimated beams for the interferometer, the beam profiles and the divergence angles have been measured for the 48- and 57-µm CH_3OD lasers oscillated simultaneously. Water vapor absorptions at 22 ^{o}C for the laser wavelengths have been measured to realize the propagation line.

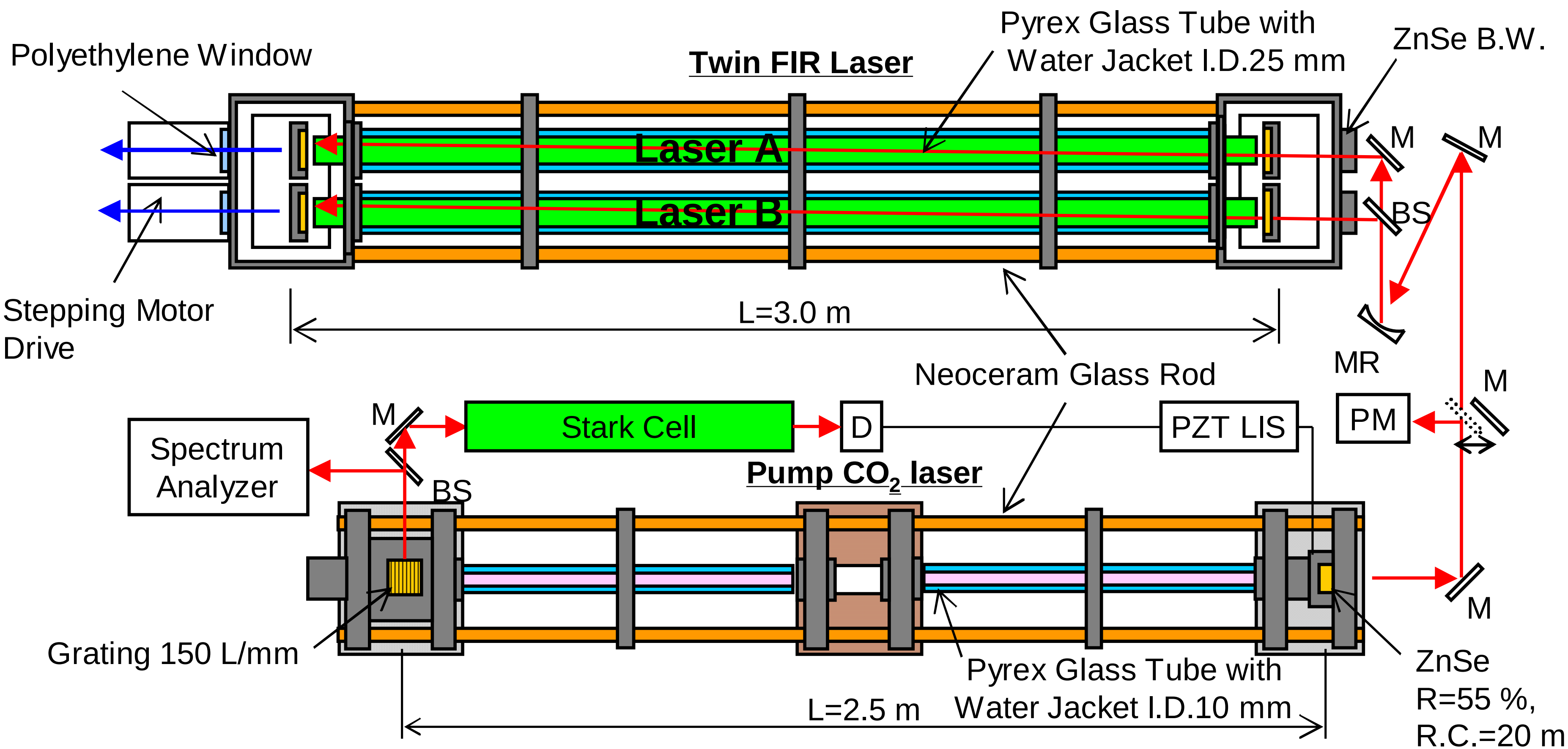
Optical constants and transmittance (reflectance) of crystal quartz, silicon, CVD-diamond, polyethylene sheet, Mylar film, TPX plate, metal mesh and wire grid have been measured to design the optical components (observation windows and beam splitters) in the 48- and 57-µm laser interferometer system.

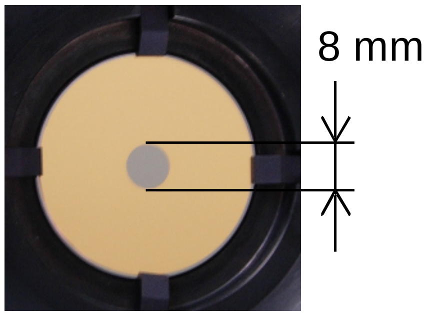
Development of 50-μm lasers

Optically pumped FIR laser system in Chubu University



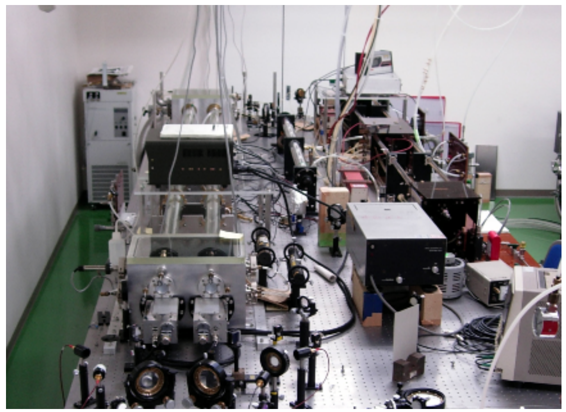
CW CO_2 laser pumped twin FIR laser system



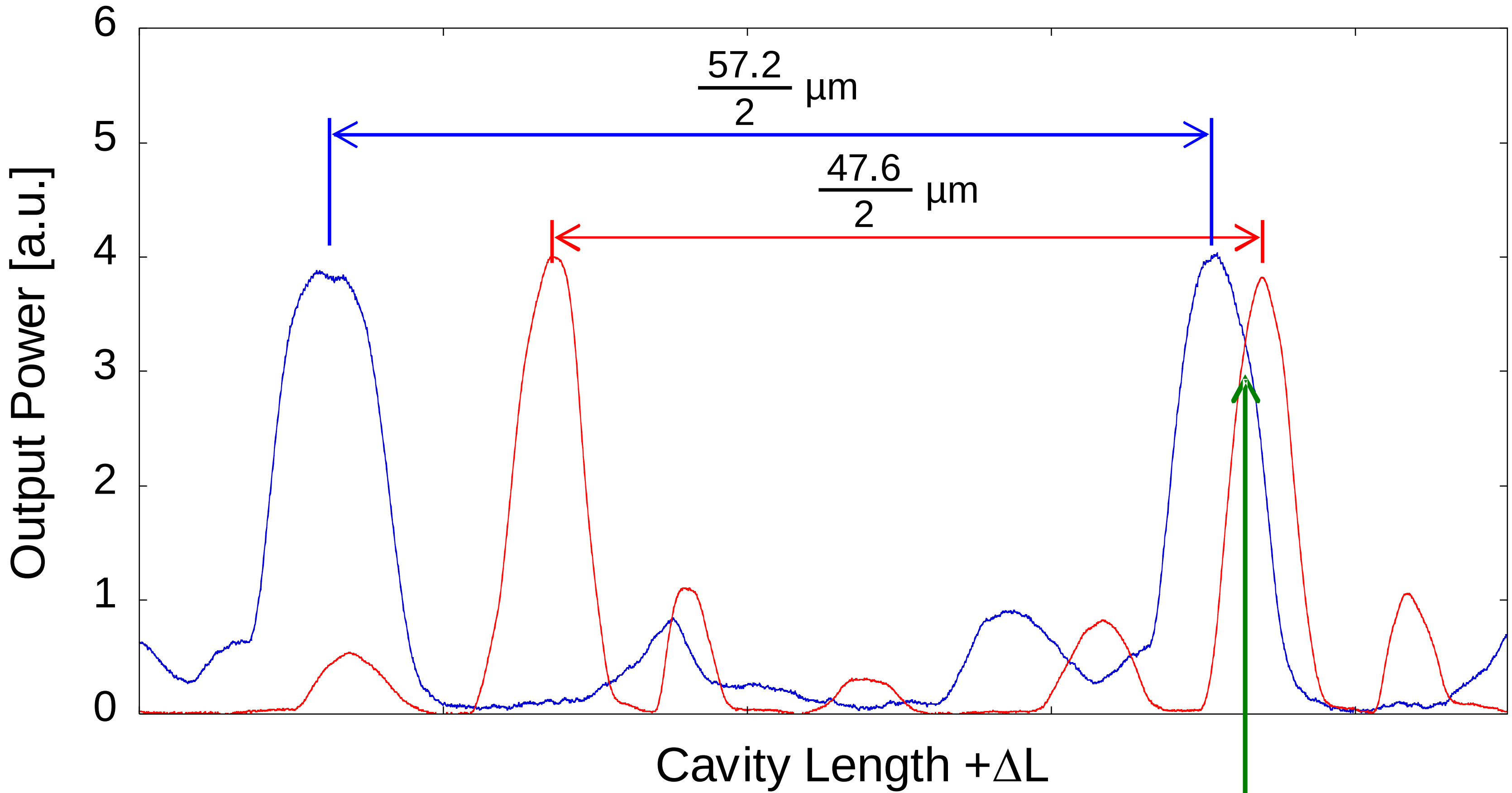


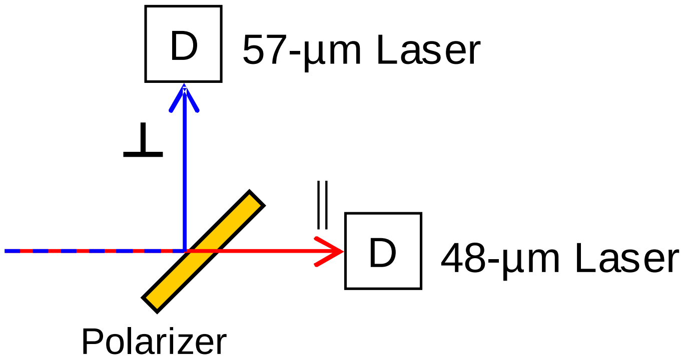
Silicon Hybrid Coupler

- CO_2 Laser Line; 9R(8)
  Power; 70 W
- FIR Laser Molecule; CH_3OD
  Wavelength; 48-, 57-µm,
  Power; ～60 mW (Pump 30 W)



Detuning curves of the 48- & 57-µm CH_3OD lasers



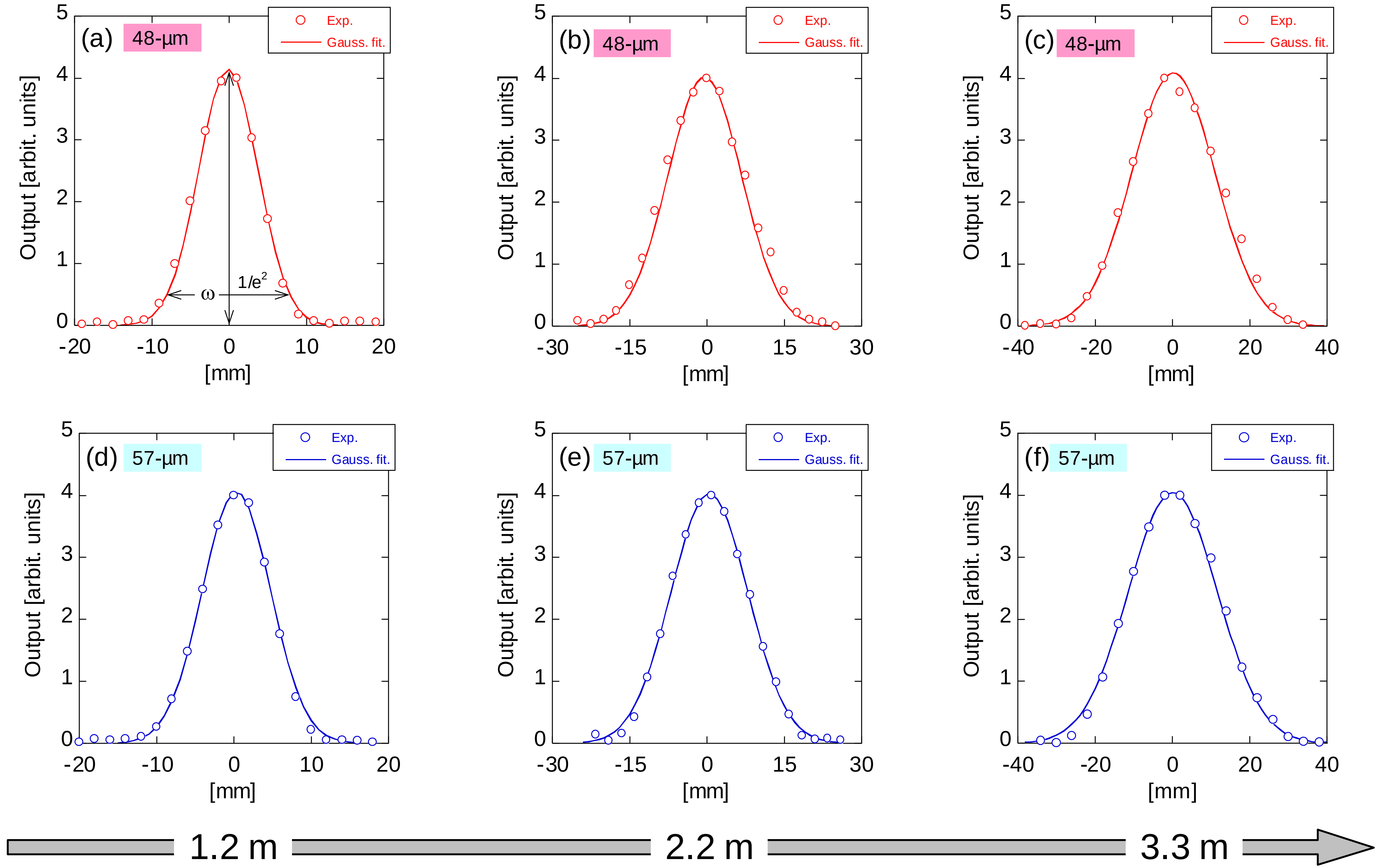


Simultaneous Oscillation

✓ Measurement of beam profiles

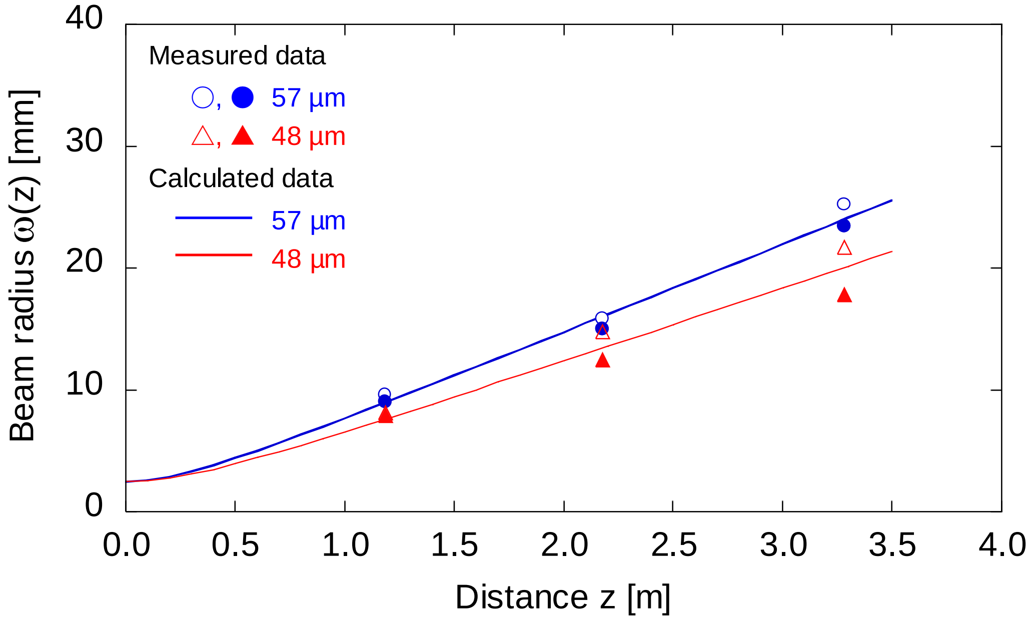
Transmission properties of 50-µm lasers

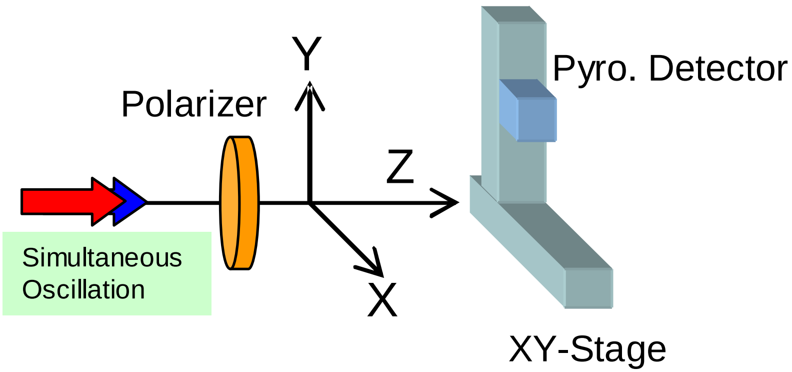
Beam profiles of the 48- & 57-µm CH_3OD lasers



Distance from the output mirror Z [m]

Beam propagations of the 48- & 57-µm CH_3OD lasers





ω: Beam radius ($1/e^2$)
z : Distance from the output mirror

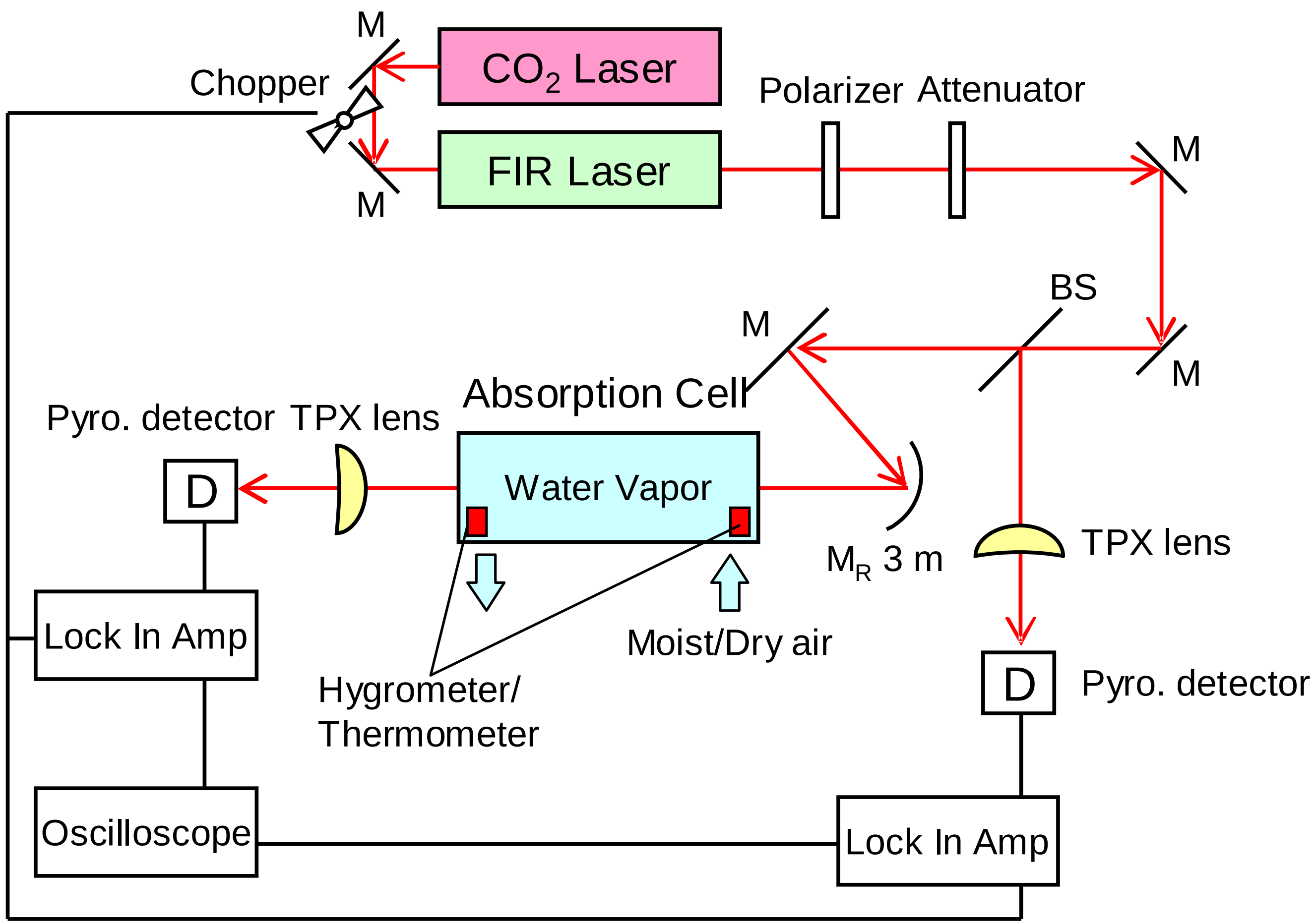
Calculated lines
Gaussian beam propagation
beam waist: $\omega_0 = 2.5$ mm
Wavelength: $\lambda_{57} = 57.1511$ µm,
$\lambda_{48} = 47.65$ µm

	Beam radius ω (mm)			
Distance z (m)	○57x	●57y	△48x	▲48y
1.2	9.6	9.0	8.1	7.9
2.2	15.9	15.0	14.8	12.5
3.3	25.2	23.5	21.7	17.8

⇩

Beam divergence θ
$\theta_{57} = 7.3 \times 10^{-3}$ rad.
$\theta_{48} = 6.1 \times 10^{-3}$ rad.

Experimental setup of water vapor absorption measurement



◆ FIR laser

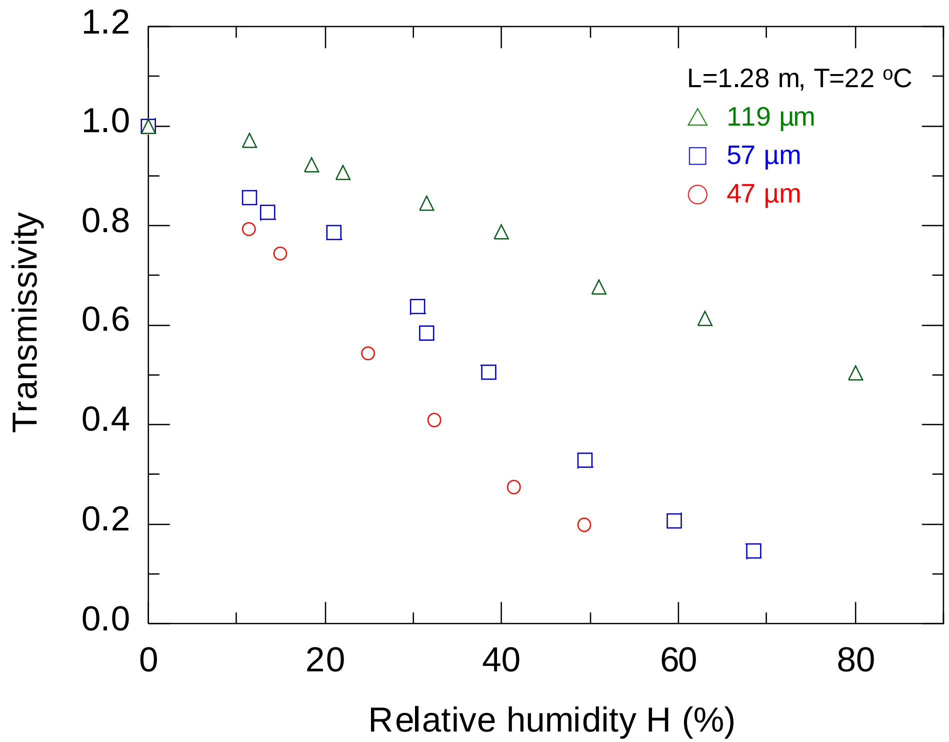
119-µm CH_3OH laser
48-µm CH_3OD laser
57-µm CH_3OD laser

◆ Absorption cell

Glass tube
Polyethylene windows
Length 1.28 m
Diameter 90 mm
Temperature 22 ^{o}C
Pressure 1 atm (except for 0 % humidity)

✓ The humidity in the cell was adjusted by a moist air and a dry air. The humidity and temperature were measured by two thermometer / hygrometer at inner both ends. The transmitted laser power after passing through the absorption cell was detected by a pyroelectric detector.

Transmissivity of the water vapor cell for 48-& 57-μm and 119-μm lasers.



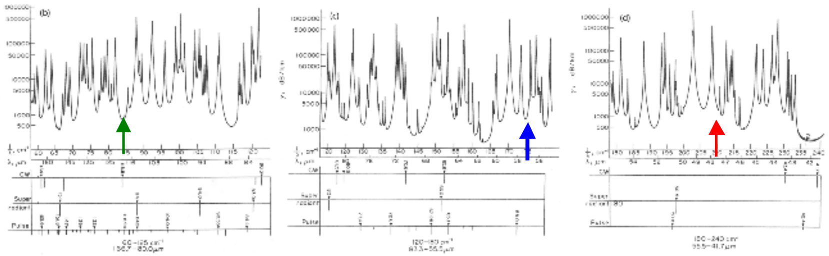
The transmissivity is normalized to 1.0 at 0 % in humidity in a vacuum.

Absorption coefficients (H = 39 % (ρ = 7.5 g/m³), T = 22 °C)

Large absorption

- 0.19 m^{-1} for 119 μm CH_3OH laser
- 0.51 m^{-1} for 57.2 μm CH_3OD laser
- 0.91 m^{-1} for 47.6 μm CH_3OD laser

Water vapor absorption in atmospheric calculated by Gallagher et al (actual vapor density ρ = 7.5 g/m³, temperature 270 K)



Absorption coefficients

∼0.18 m^{-1} @ 84.2 cm^{-1}(119 μm)
∼0.46 m^{-1} @ 175 cm^{-1}(57.2 μm)
∼0.46 m^{-1} @ 210 cm^{-1}(47.6 μm)

Ref. J. J. Gallagher *et al*., Infrared Physics **17**, 43 (1977)

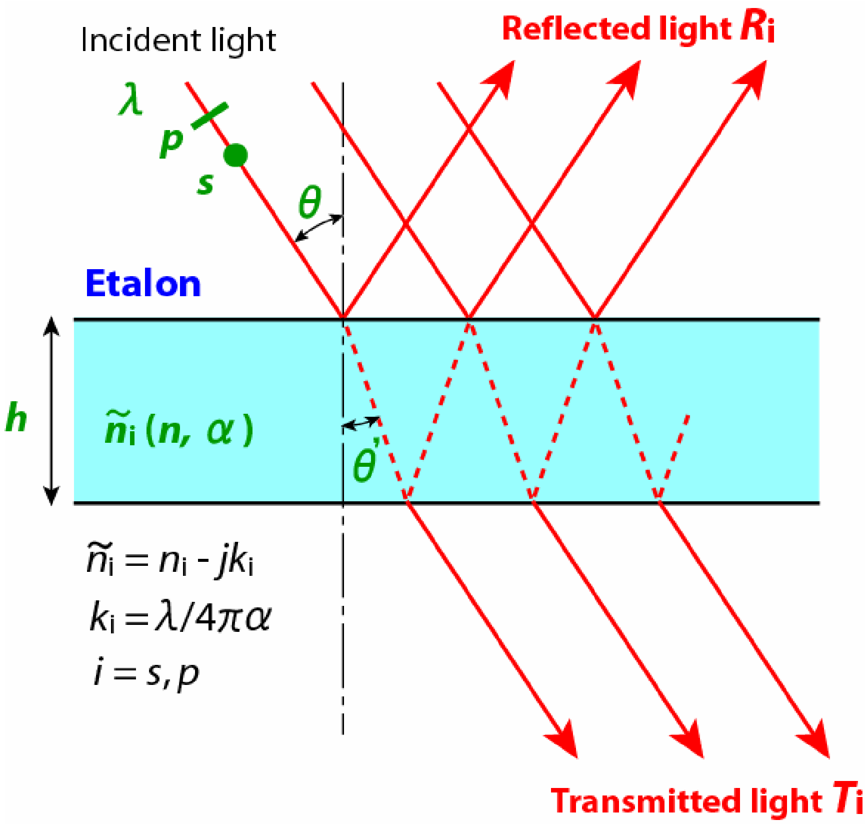
Attenuations by water vapor absorption in the air (H = 11.5 %, T =22 °C)

Transmission Distance [m]	Attenuation [%]	
	48 μm	57 μm
5	57	38
10	81	62

It is therefore very important to eliminate humidity when using the 48- and 57-μm lasers.

Optical elements for 50-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

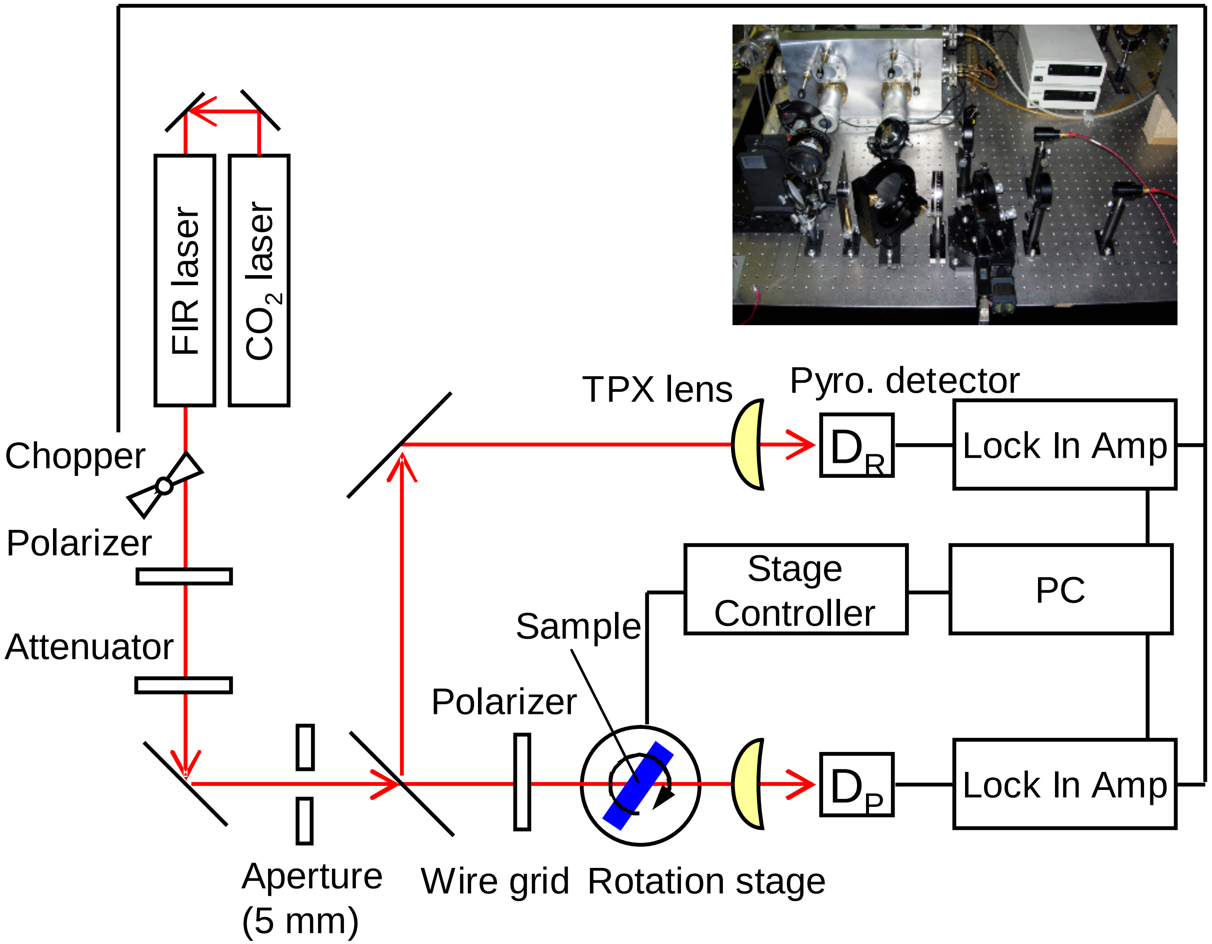
λ, h, θ, T ⇨ n, α

<u>119-µm laser interferometer on the LHD</u>

Optical constants of Qu for a 119 µm laser were measured by this method.

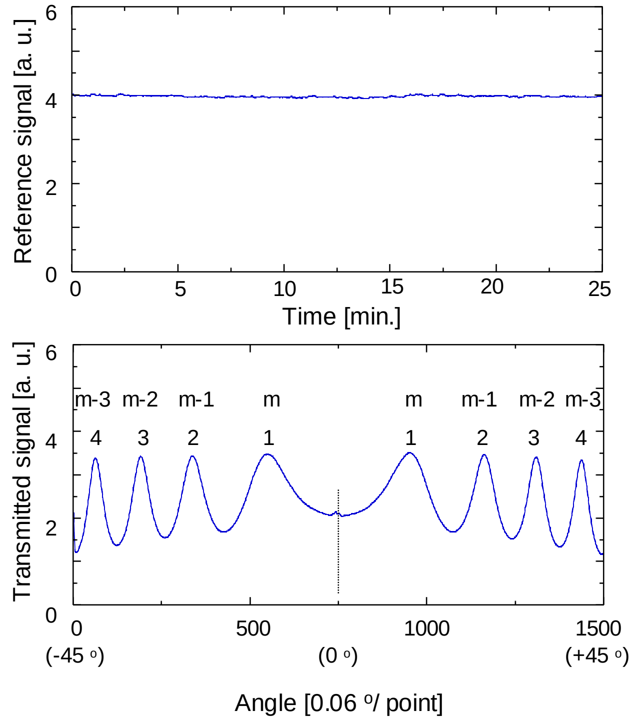
The windows and beam splitters of Qu were designed.

Experimental setup of optical constants measurement



Incident angle: -45 - +45 deg.
Resolution of the rotary stage: 0.06 deg.
Measurement time: about 30 min.
Output stability of FIR lasers: ±1 % / 30 min.

Example of measurement data



- Refractive index

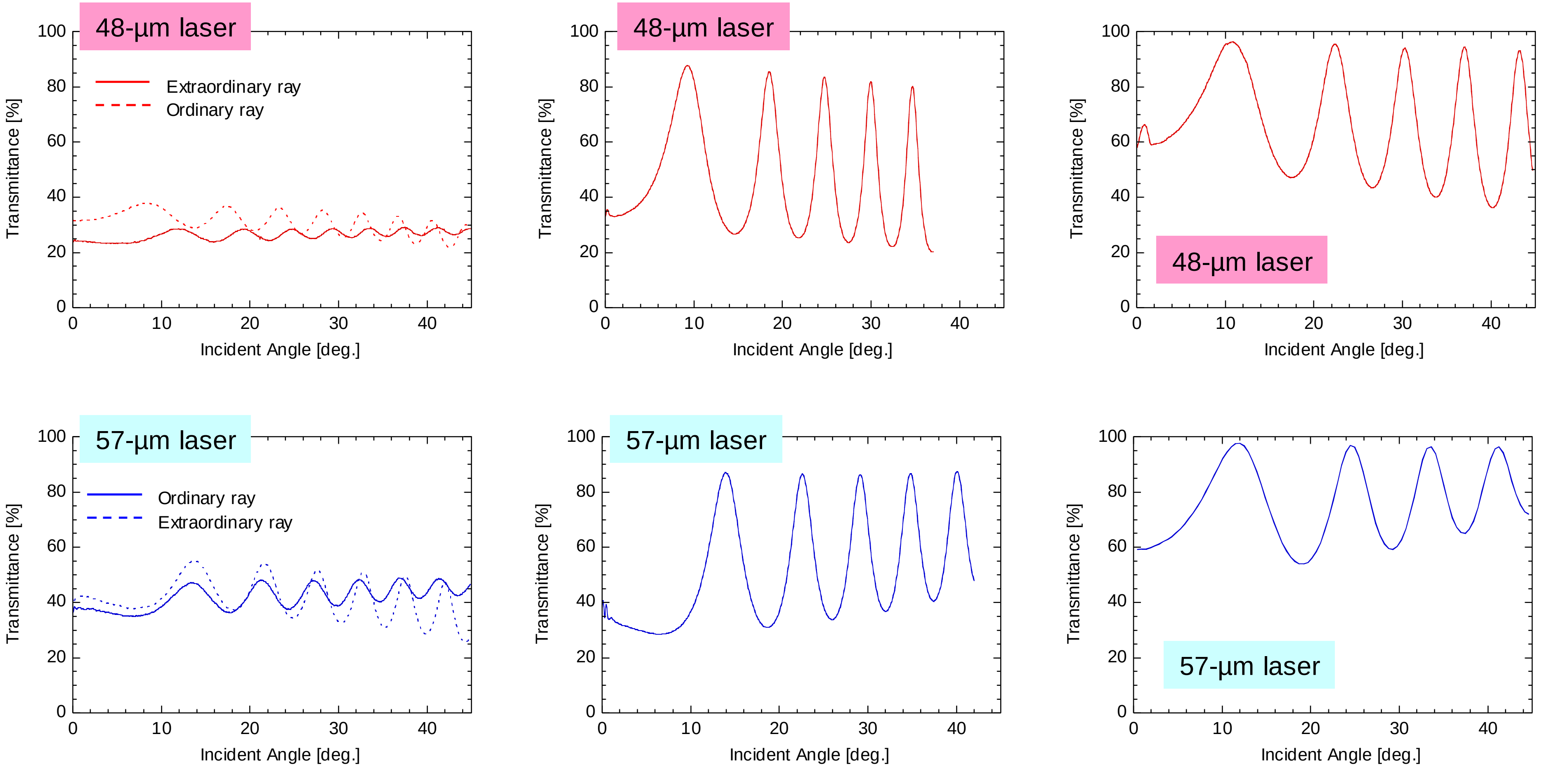
⇨ $$n = \left(\frac{\lambda^2}{4\pi h} (\mathrm{m} - \mathrm{p} + 1)^2 + \sin^2 \theta) \right)^{\frac{1}{2}}$$

- Absorption coefficient

⇨ Transmittance of the first peak

Transmittance of etalons for the 48- & 57-μm lasers

Qu (h=1.5845 mm) | Silicon (h=2.1718 mm) | CVD-Diamond (h=1.023 mm)



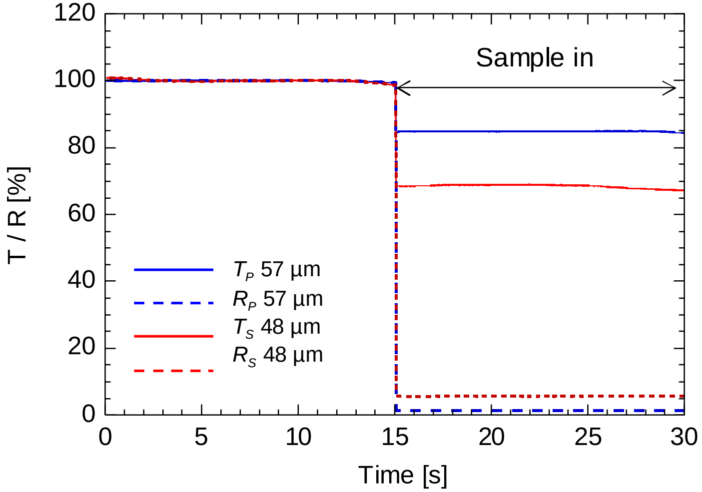
Refractive Index *n* and Absorption Coefficient α of Qu, CVD-diamond, and Si for the 48- & 57-μm lasers

Sample	57.1511 μm		47.65 μm	
	n	α [cm^{-1}]	*n*	α [cm^{-1}]
Crystal Quartz*	2.1765 ± 0.0002	3.8 ±0.1	2.219 ± 0.001	6.4 ± 0.2
Crystal Quartz**	2.2306 ± 0.0002	2.9 ± 0.1	2.260 ± 0.001	4.9 ± 0.2
CVD-Diamond	2.383 ± 0.002	0.19 ± 0.05	2.383 ± 0.002	0.25 ± 0.05
Silicon	3.4164 ± 0.0005	0.36 ± 0.05	3.416 ± 0.001	0.33 ± 0.05

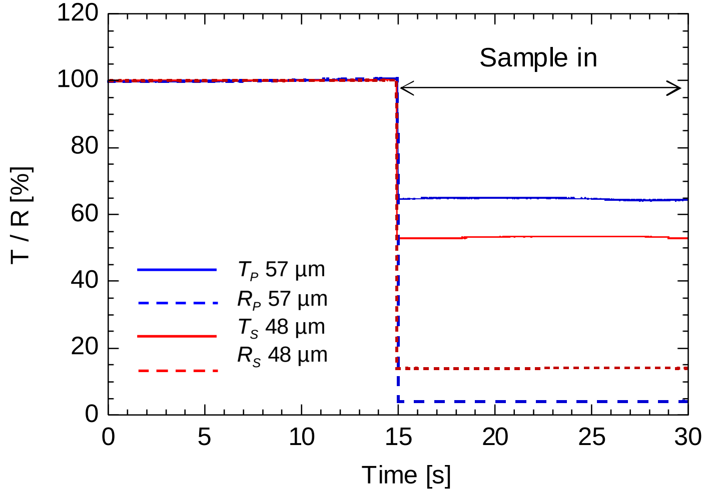
- Crystal Quartz: Thickness 1.5845 mm, *Ordinary-ray, **Extraordinary-ray
- CVD-Diamond: Thickness 1.023 mm
- Silicon: Thickness 1.5845, 2.1718, and 1.5452 mm, Resistivity 2.8 kΩcm, Temperature 20 ^{o}C

Transmittance *T* and reflectance *R* of polyethylene, TPX, Mylar, metal mesh at 45 ° incidence for the 48- & 57-μm lasers

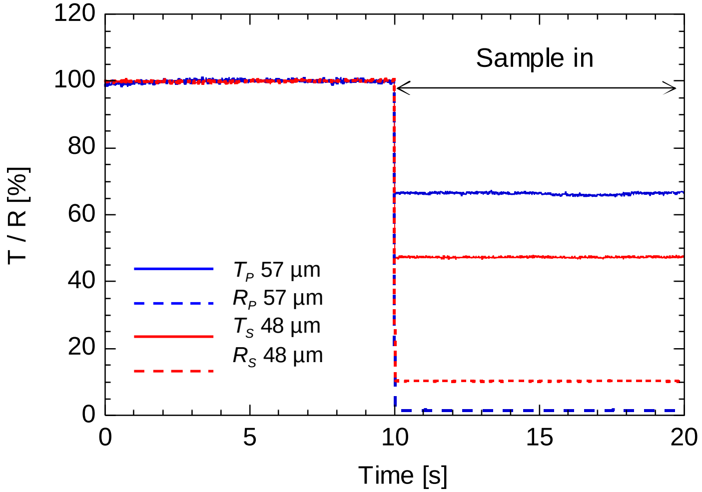
Polyethylene sheet



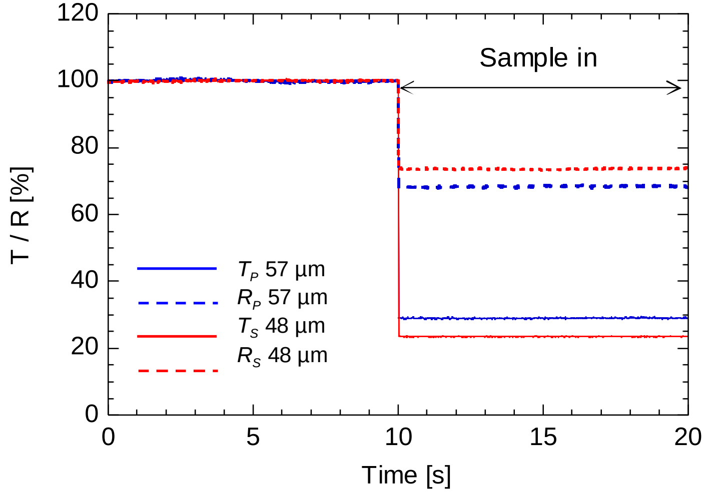
Mylar film



TPX plate



Metal mesh



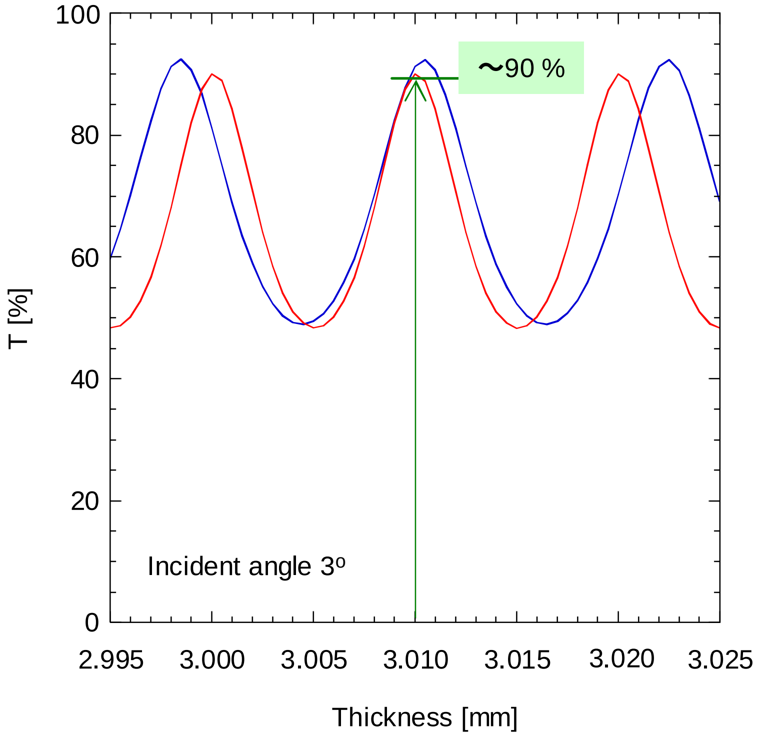
Transmittance *T* and reflectance *R* of Polyethylene, TPX, Mylar, Metal Mesh, and Wire Grid at 45 ° incidence for the 48- & 57-µm lasers

Sample	57.1511 µm		47.65 µm	
	Tp [%]	*Rp* [%]	*Ts* [%]	*Rs* [%]
Polyethylene	85	1	70	6
TPX	66	2	47	10
Mylar	64	4	51	14
Metal Mesh	29	68	23	74
Wire Grid	93	2	89	6

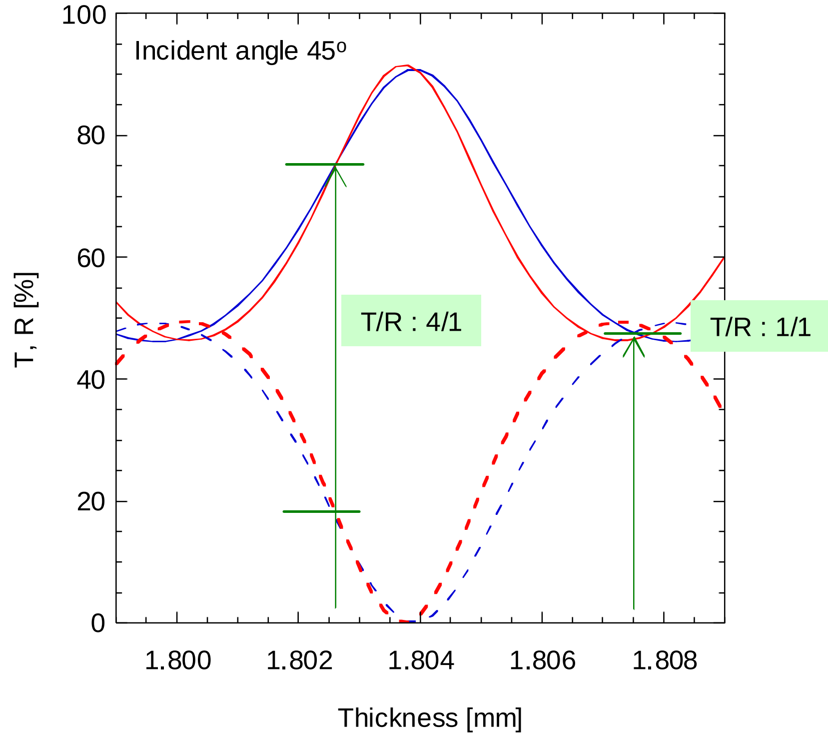
- Polyethylene sheet: Thickness 0.9 mm
- TPX plate: Thickness 3.06 mm
- Mylar film: Thickness 0.05 mm
- Metal Mesh: Wire Width 7.4 µm, Hole Size 18 µm
- Free Standing Wire Grid: Wire Diameter 5 µm, Wire Spacing 12.5µm,
  The elected filed of the laser is perpendicular to the wire.

Example designs of optical elements for the 48- & 57-μm lasers

CVD-diamond window



Silicon beam splitter



T λ= 57.1511 μm
(p-polarized light, n=2.383, α=0.19 cm^{-1})
T λ= 47.65 μm
(p-polarized light, n=2.383, α=0.25 cm^{-1})

T λ= 57.1511 μm
R (p-polarized light, n=3.4164, α=0.36 cm^{-1})
T λ= 47.65 μm
R (p-polarized light, n=3.416, α=0.33 cm^{-1})

Summary

- **<u>Short-wavelength FIR Lasers</u>**

  To design collimated beams for the two-color laser interferometer using 48- and 57-µm CH_3OD lasers, the intensity profiles have been measured in the simultaneous oscillations. The beam divergence angles for the 48-laser and 57-µm lasers have been found to be 6.1×10^{-3} rad and 7.3×10^{-3} rad, respectively.

  Water vapor absorptions of the 48- and 57-µm lasers have been measured. The absorption coefficients at 22 ^{o}C and 39% have been 0.91 m^{-1} for the 48-µm laser and 0.57 m^{-1} for the 57-µm laser. It has been found that a sufficient or a complete dehumidification is necessary for a long distance transmission of the 48- and 57-µm lasers.

- **<u>Optical Elements for 50 µm lasers</u>**

  We have measured optical constants (n, α, T, and R) of crystal quartz, silicon, CVD-diamond, polyethylene, Mylar, TPX, metal mesh, and wire grid for the 48- and 57-µm lasers. It has been found that CVD-diamond and high resistive silicon etalons are suitable material as observation windows and beam splitters in the interferometer.