Determination of FIR Laser Wavelength Using Precise Refractive Index Measurement Method of Optical Etalon

K. Nakayama[a], A. Matsubara[a], T. Kaneba[a], S. Okajima[a], K. Kawahata[b], T. Tanaka[b], T. Tokuzawa[b], T. Akiyama[b], and H. Ohkuma[c]
[a] Chubu University, 1200, Matsumoto-cho, Kasugai-shi, Aichi, 487-8501, Japan
[b] National Institute for Fusion Science, 322-6, Oroshi-cho, Toki-shi, Gifu, 509-5292, Japan
[c] Japan Synchrotron Radiation Research Institute, 1-1-1, Kouto, Sayo-cho, Sayo-gun, Hyogo, 679-5198 Japan

Abstract— A far-infrared (FIR) laser wavelength has been determined from refractive index of silicon with high resistivity (~2.8 kΩ-cm). A wavelength of a 48-μm CH_3OD laser pumped by continuous wave (cw) 9R(8) CO_2 laser has been measured at five significant figures. The wavelength and the refractive index are 47.661 ± 0.005 μm and 3.4147 at 9.6 °C, 3.4164 at 19.4 °C, and 3.4180 at 28.8 °C. A known wavelength of a 97-μm CH_3OH laser pumped by cw 9R(10) CO_2 laser has been also measured by using this technique.

I. Introduction

Far-infrared (FIR) lasers have been utilized as optical sources for various measurements. We have developed a two color interferometer using 48- and 57-μm CH_3OD lasers pumped by cw 9R(8) CO_2 laser for high density operation of the large helical device (LHD) and for future fusion devices such as ITER[1]. Many optical windows and beam splitters with various transmission and reflection ratio are used in this system. These designs require the wavelength, the refractive index, and the thickness of five significant figures, while it also needs the absorption coefficient of two significant figures. We selected a high resistive silicon etalon as the optical elements, because the absorption is low in the wavelength region from 40 μm to 70 μm. The precise frequency (wavelength) of the 57-μm laser (57.1511 μm) has been already reported[2], while the wavelength of the 48-μm laser (47.65 ± 0.06 μm) has been proven only at the precision of four figures[3]. Therefore we have measured precise optical constants of silicon using three FIR laser lines with the known wavelength, and the wavelength of the 48-μm laser has been determined from the refractive index.

II. Experimental

The optical constants have been obtained from the measurements of transmitted light by multiple reflection of a rotating silicon etalon[4]. FIR laser wavelengths have been measured by using the same system. A schematic diagram of the experimental setup is shown in Fig. 1. The silicon is resistivity about 2.8 kΩ-cm (Shin-Etsu Chemical Co., Ltd.). The silicon etalon polished both sides had a flatness of $\lambda/2$ for visible light (632.8 nm). We used four silicon etalons with different thickness. These samples were 1.5441, 2.1704, 2.1708, and 2.1718 mm thick and had an uncertainty in thickness of ±0.2 μm at the area used for measurements. The thickness was measured by two linear gages with a resolution of 0.1 μm. Three FIR lasers of 57-μm CH_3OD laser (57.1511μm), 71-μm CH_3OH laser (70.5116 μm), and 119-μm CH_3OH laser (118.834 μm) are used to measure optical constants of silicon. Frequences of these lasers are precisely obtained by the heterodyne technique of mixing FIR laser radiation and other oscillators[2, 5]. The sample is set on a rotation stage. The transmitted signal as shown in Fig 2 is obtained by changing the incident angle to the etalon. From the equation of an etalon by multiple reflections[6], the transmission peaks satisfies

$$2nh\cos\theta' = (\mathrm{m} - \mathrm{p} + 1)\lambda, \tag{1}$$

$$\theta' = \sin^{-1}\left(\frac{\sin\theta}{n}\right), \tag{2}$$

where n is the refractive index, h is the etalon's thickness, m is the interference order of the first peak, p is the peak number, λ is the laser wavelength, θ' is the refracting angle, and θ is the incident angle. The refractive index is decided from the average of the refractive indices of each transmission peaks when the standard deviation for any m value becomes a minimum. To put it another way, it is possible to determine the laser wavelength from the refractive index, the thickness, and the incident angle of the transmission peak as shown in Table I.

III. Results and Discussion

The refractive index of silicon for each FIR laser line at 10, 19, and 29 °C are shown in Fig. 2[4]. The refractive index depends strongly on temperature, while the wavelength dependence is small. These properties were presented by Afsar et al.[7], also. To demonstrate this wavelength measurement

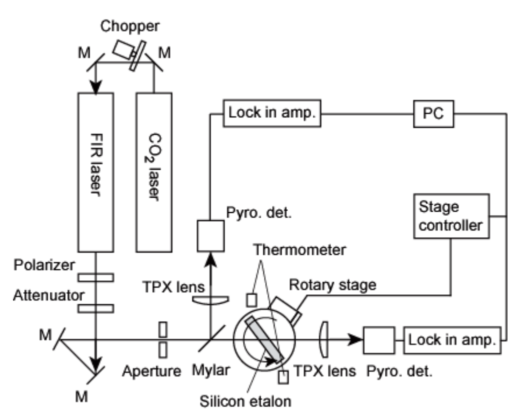

Fig. 1. A schematic diagram of the experimental setup.

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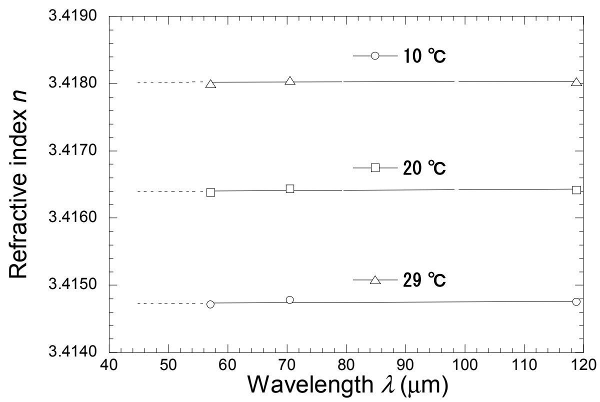

Fig. 2. Refractive index of silicon at 10, 20, and 29 °C for 57- and 71-and 119-μm FIR lasers.

Table I. Determination of the 97-μm CH_3OH laser wavelength (h =2.1708 mm, n =3.4166 at 20.3 °C).

Peak No.	Wavelength λ [μm]		
	m=152	m=153	m=154
1	97.157	96.522	95.896
2	97.162	96.523	95.892
3	97.165	96.522	95.887
4	97.169	96.522	95.882
Average	97.163	<u>96.522</u>	95.889
S.D.	0.006	0.001	0.007

method, we experimented about a 97-μm CH_3OH laser (96.5224 μm) pumped by 9R(10) CO_2 laser, the precise wavelength of which was known[5]. The refractive index of around 96.5 μm in wavelength was estimated at n=3.4166 at 20.3 °C by interpolation. The refractive index change of Δn=0.0001 correspond to the temperature change of Δt=0.6 °C. Consequently, the temperature during measurement was controlled within Δt=0.3 °C. Figure 3 shows the transmittance of the silicon etalon as a function of the incident angle. The transmission peak by multiple reflections appears. Table I shows the process of the determination of the wavelength. This calculation demands the etalon's thickness and the refractive index of five figures. The wavelength of the 97-μm laser was measured to be 96.522 ± 0.005 μm. The result clearly shows that this method makes possible precise wavelength measurements at five significant figures. In the same way, we measured the 48-μm laser wavelength. The refractive indexes at various temperatures are at 3.4147 at 9.6 °C, 3.4164 at 19.4 °C, and 3.4180 at 28.8 °C. These refractive indices were estimated by extrapolation, because refractive index of silicon did not have a drastic change in the region from 40 to 120 μm[7]. The 48-μm laser wavelength was determined at 47.661 ± 0.005 μm as shown in Fig. 4. This indicates that windows and beam splitters can be designed by using these values. In the present work FIR laser wavelengths have been determined by using precise refractive index measurements. A silicon etalon with high resistivity is useful for the application. This method is simple, and does not need other local oscillators.

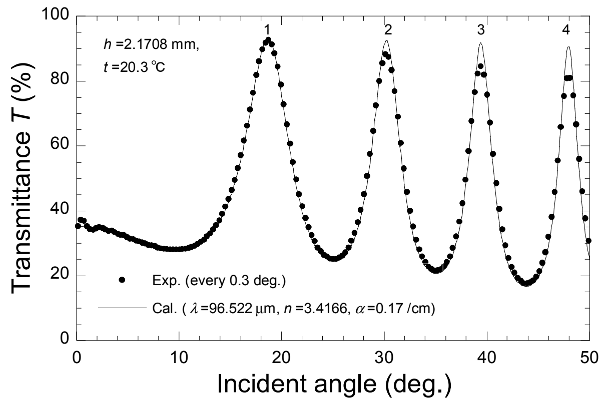

Fig. 3. Transmittance of the silicon etalon as a function of the incident angle for the 97-μm CH_3OH lasers.

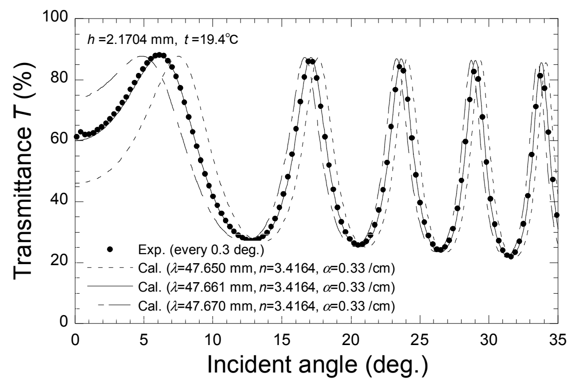

Fig. 4. Transmittance of the silicon etalon as a function of the incident angle for the 48-μm CH_3OD lasers.

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