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Length Measurement of Gauge Blocks Using a 3.39 μm He–Ne Laser Interferometer

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An infrared interferometer is described for length measurement which uses a simply stabilized 3.39 μm He–Ne laser as a light source and has a piezoelectric-transducer scanning system for recording interference fringes of two fields of view simultaneously and automatically. Pointing accuracy of the order of interference obtained is estimated to be 0.5° in phase.

Using this interferometer, the refractive index of air at a wavelength of 3.39 μm is measured with an accuracy of 3×10^{-8} and Edlén's dispersion formula is confirmed with an accuracy of less than one part in 10^7. The length of a gauge block of nominal length 200 mm is measured with an accuracy of 5×10^{-8} in standard deviation.

§1. Introduction

Interferometry has recently been indispensable in the precise measurement of length. The two types of method used are a fringe counting method and an excess fraction method. The former can measure distances up to a few meters, but requires a translation mechanism for precise mirror-movement and its application is limited. On the other hand, the latter does not require such a mechanism, but its application is confined to lengths up to several tens of centimeters because no source which emits coherent multiwavelength light exists.

Infrared interferometry is of great interest in length measurement since the wavelength is long and the determination of length is possible by measuring the fractional order of interference using only one wavelength. It is profitable for long-distance measurement because the signal-to-noise ratio of the interference fringe is hardly decreased even in air turbulence and mechanical vibration. A 3.39 μm He–Ne laser has been stabilized with a reproducibility of less than 1×10^{-10} using a methane molecule[1,2] and its wavelength was recommended by the Comité Consultatif pour la Définition du Métre (CCDM).[3] Therefore, the 3.39 μm He–Ne laser can be utilized for accurate measurement of length.

The purpose of this paper is to investigate the infrared interferometry for length measurement. The 3.39 μm He–Ne laser interferometer with a piezoelectric transducer (PZT) for scanning the interference fringes[4] was developed and could simultaneously record two kinds of fringes, so that it eliminated the error sources, namely, variations of temperature, refractive index of air, laser wavelength and, in particular, nonlinearity of PZT in scan.

§2. Principle of Measurement

2.1 *Infrared laser*

The 3.39 μm He–Ne laser used in this study operates with a Spectra Physics model 120 tube which has a cold cathode and an electric power supply. The cavity is constructed with thermally insensitive material (invar) and is designed to cancel out the thermal expansion of the invar. The mounts of the PZT and the mirrors are made of aluminum, and they jut out into the inside of the cavity.[5] The thermal drift of the output power of the laser was very small and its wavelength was nearly fixed during experiment because the whole experiment requires only a few minutes. The typical output power of the laser is about 1.2 mW. The PZT changes the cavity length so that the laser may oscillate at the top of the gain curve with the TEM_{00} mode. The resettability of the wavelength of this laser is estimated to be 3×10^{-8} in standard deviation from the error voltage applied to the PZT.

The TEM_{00} mode oscillation of the laser was confirmed by scanning the section of the laser beam with an aperture 0.4 mm in diameter, in the rear of which the InAs detector was positioned. Scanning of the beam was achieved by a rotating mirror. Figure 1(a) shows an oscillograph picture of the intensity distribution of the transverse mode pattern of the laser.

The cavity length of the laser is about 43 cm and the laser may operate in longitudinal modes up to three because the Doppler width of the 3.39 μm laser is several hundred megahertzs. Therefore, the confirmation of one mode operation near the center of the output curve was achieved by using the infrared interferometer described later. In the interferometer illuminated by the j-mode laser, the visibility of interference fringes becomes nearly zero at the optical path difference of two j-ths of the cavity length. Next, the laser frequency is scanned by applying a voltage to the cavity PZT, and then the output power of the laser and the interference fringe phase at a fixed path difference are varied. Figure 1(b) shows a typical recorder graph of the output curve and the fringe signal at a path difference of about 20 cm as a function of laser frequency. The region of one mode oscillation is evident from the fringe signal.

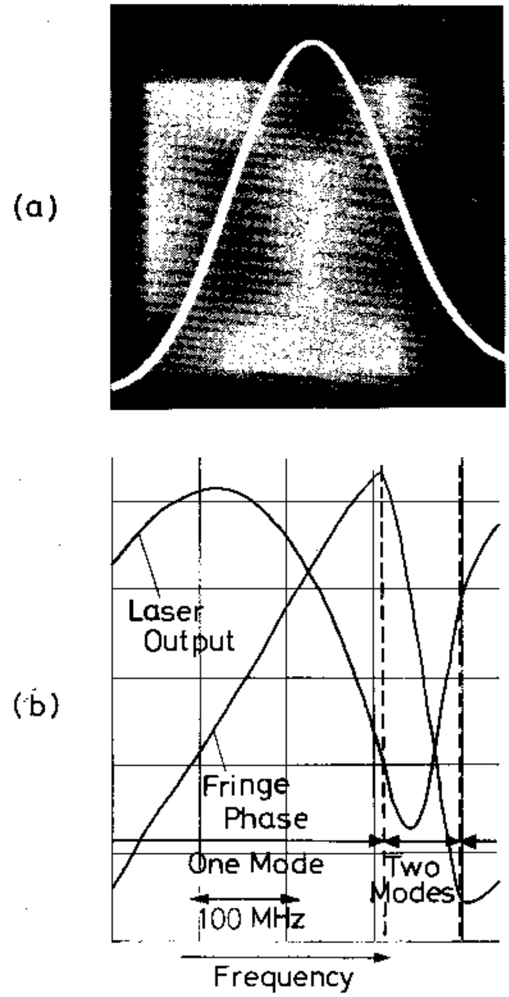

Fig. 1. Properties of the 3.39 μm He–Ne laser: (a) the transverse intensity distribution of the laser beam; (b) the output power curve of the laser and the profile of the interference fringe intensity at a path difference of about 20 cm as the resonator is tuned.

2.2 *Infrared interferometer*

A block diagram of the infrared interferometer for automatic recording of interference fringes is shown in Fig. 2. The interferometer is aligned by using the 0.633 μm He–Ne laser VL. The beam from the 3.39 μm He–Ne laser IR is arranged in accordance with the beam of VL at the metal-film mirror T which transmits the visible light but does not transmit the infrared light. The beams are converged by the spherical mirror Cl of focal length 38 mm and collimated by the off-axis paraboloidal mirror C2 of focal length 770 mm through the aperture P, so that the diameter of the beam is magnified by a factor of 20. The beam splitter B is a dielectric-coated fused-quartz plate and is slightly transparent in the visible region, so that the interferometer can be adjusted with the aid of a 0.633 μm He–Ne laser. The mask F, which has three holes 8.0 mm in diameter as shown in Fig. 3, is used for selecting the fringe fields. Fringe intervals are aligned to be 10 times as large as the diameter of the mask hole. These fringes are focused by the identical lens O of focal length about 200 mm. The outer and inner fringes are separated by the prism S and these fringes are detected with the PbS elements D1, D2, respectively.

For suppressing the back-talk effect of the laser,[6,7] the beam reflected from the interferometer is arranged to make an angle 2θ with the incidence beam. The aperture, which is a hole 0.3 mm in diameter, elliminates the effect by stopping the reflected beam. In the measurement of length L, the correction of $L\theta^2/2$ is needed for the so-called cosined error.

If only the same mask with holes, one of which is sized to a gauge block, is used in the measurement of wavelength of light and length there is no necessity to make the correction of diffraction for the measured values.

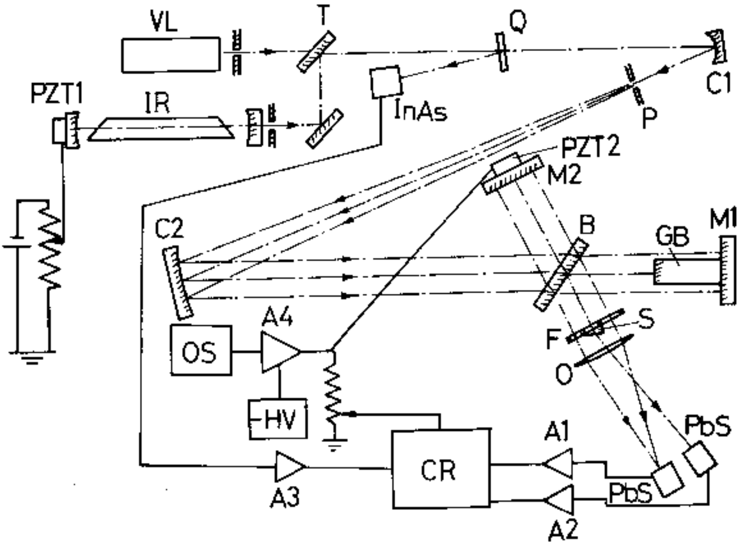

Fig. 2. Automatic *ir* laser interferometer. IR, 3.39 μm laser. VL, visible laser. PZT1, PZT2, piezoelectric transducers. T, mixer. Q, quartz plate. C1, concave mirror. P, aperture. C2, offaxis paraboloidal mirror. B, beam splitter. GB, gauge block. M1, base plate. M2, reference mirror. F, mask. S, prism. O, lens. A1 to A4, amplifiers. OS, oscillator. CR, chart recorder.

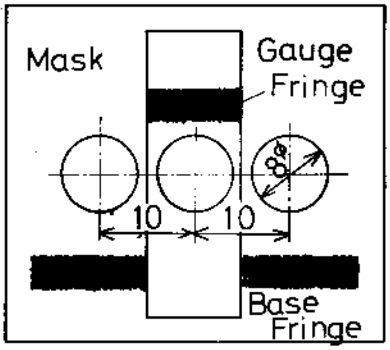

Fig. 3. Field of view of the interferometer and the mask for selecting the fringe field.

2.3 *Electronic circuit*

For scanning the interference fringes, the sawtooth signals from the very-low-frequency oscillator OS (typically 0.05 Hz) are amplified and applied to the PZT. The amplitude of the scan is about 1.4 fringes.

The output power of the infrared laser is detected with the InAs element, and then the output voltage signal is amplified by a simple linear circuit. The fringe signals from the PbS are amplified by a differential circuit to eliminate the bias current. Using this method, the signals with a good signal-to-noise ratio were obtained without using a lock-in amplifier (see Fig. 4).

2.4 *Procedure of reading the interference fringe*

At first, the cavity length of the infrared laser is varied by the cavity PZT so that the laser may oscillate at the top of the laser gain in a single longitudinal mode. Next, the interference fringe signals which are produced by the operation of the interferometer PZT are recorded by the chart recorder CR.

To avoid nonlinearities of the PZT in scan, the following technique was used.[4)] The interference fringes from the base plate and the gauge block are simultaneously recorded as shown in Fig. 4 and their phases are determined by using the equation

$$\phi=\sin^{-1}\left(2\frac{I(\phi)-I_0}{I_M-I_m}\right), \tag{1}$$

where $I(\phi)$ is the intensity at the point of measurement, I_M and I_m are the maximum and minimum intensities, respectively, and I_0 is the mean intensity. Denoting by subscripts 1 and 2 the quantities which refer to the phases of their fringes, the difference $\Delta\phi$ between their fringe phases is given by $(\phi_1-\phi_2)$. The refractive index of air is measured in the same way.

§3. Measurement

3.1 *Refractive index of air*

For measuring the refractive index of air at

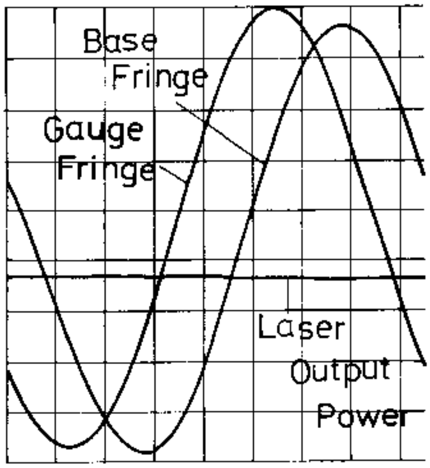

Fig. 4. Typical examples of the interference fringe and the laser output power recorded by the chart recorder.

the wavelength of 3.39 μm, the vacuum chamber cells of lengths 200 mm and 500 mm are used with the infrared interferometer and are shown schematically in Fig. 5. The windows of the cells are made of fused quartz. The insides of the cells are kept at a high vacuum of less than 0.02 Torr (3 Pa).

The refractive index n of air is described by

$$n-1=(m_n+\Delta\phi/360)\cdot\lambda/2D, \qquad (2)$$

where m_n is an integer, D the cell length and λ the vacuum wavelength. The phase difference $\Delta\phi$ is measured by the method mentioned before using the mask shown in Fig. 5. Then, m_n is determined as follows: when air was leaked into the cell of length 200 mm until the pressure inside it equalled atmospheric, the train of fringes produced is counted with a chart graph and n is measured with an accuracy of about 2×10^{-6}.[4] Next, using the same cell, the value of n is determined to an accuracy of 2×10^{-7} from the phase measurement. Finally, the accuracy is elevated to an accuracy of 3 parts in 10^8 with the longer cell. In this case, the phase difference $\Delta\phi$ is determined with a standard deviation of 1°, while the length D of the cell is measured with an accuracy of 10 μm.

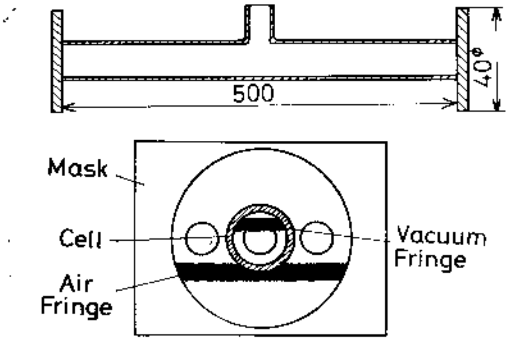

Fig. 5. Schematic diagram of one of the vacuum chamber cells used for measuring the refractive index of air and the field of view of the interferometer.

In length measurement, it is very convenient to use Edlén's dispersion formula[8] because of its simplicity. However, the formula was not confirmed for wavelengths above 2 μm. Under normal conditions, the formula is given by

$$(n-1)\times10^{-6}=267.51-0.915(t-20) + 0.352(p-760)-0.057(f-10), \qquad (3)$$

where t is the air temperature in °C, p the atmospheric pressure in Torr, and f the humidity in Torr.

In a controlled room, the temperature, pressure and humidity can be measured with accuracies of 0.01°C, 0.05 Torr (7 Pa) and 0.2 Torr (27 Pa), respectively. Therefore, the overall accuracy of measurement of the refractive index of air is better than 5×10^{-8} when the formula is used. The difference between the values n_i measured by the interferometer and the values n_j determined by the formula are shown in Fig. 6. As is evident from Fig. 6, the refractive index at 3.39 μm was measured with an accuracy better than 1×10^{-7} using the dispersion formula. This accuracy is good enough for length measurement.

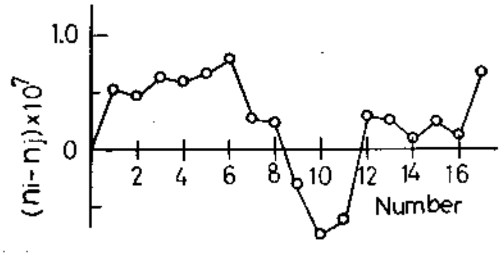

Fig. 6. The differences between the refractive indices of air measured by the interferometer (n_i) and determined by Edlén's dispersion formula (n_j).

3.2 *Gauge block*

The length L of the gauge block is given by

$$L=(m_g+\Delta\phi/360)\cdot\lambda/2n, \qquad (4)$$

where m_g is a known integer either from its history or from another measurement and $\Delta\phi$ is measured experimentally. No phase correction on reflection is needed since the gauge block and the base plate are made of identical material and their surface roughness is similar.

The gauge block of nominal length 7 mm was measured for studing the pointing accuracy of the order of interference because the effects due to temperature, wavelength in air and vibration were very small. The phase of the order of interference could be determined with an accuracy of 0.5° in standard deviation. The length of the gauge block is calculated to be 7000.053 μm with a standard deviation of 0.006 μm. The discrepancy between this value and the value obtained with a gauge block interferometer usable in the visible region[9)] was 0.003 μm.

The gauge blocks of nominal lengths 75 mm and 200 mm were measured. In the measurement of long gauge blocks, the correction of temperature is important. The measurement system is as follows: the temperature of a copper block soaked in the paraffin is used as a reference point of temperature near 20°C and measured with a quartz thermometer (Hewlett-Packard model 2810A). The temperature of the gauge block is evaluated by measuring the small difference between the temperatures on the gauge block and the copper block with a copper-constantan thermocouple and a galvanometer. The accuracy of this system is estimated to be 0.003°C.

Equation (4) is converted to

$$\begin{aligned}\lambda &= 2nL/m\\ &= 2(n_0+\Delta n)(L_0+\Delta L)/(m_0+\Delta m)\\ &= \lambda_0\left(1+\frac{\Delta n}{n_0}+\frac{\Delta L}{L_0}-\frac{\Delta m}{m_0}\right),\\ \lambda_0 &= 2n_0L_0/m_0, \qquad (5)\end{aligned}$$

where λ_0 is the reference wavelength which equals that of the methane-stabilized laser in vacuum recommended by CCDM, L_0 the length at 20°C obtained with the visible interferometer mentioned before, n_0 the refractive index of air under normal conditions and m_0 the order of interference. Then, let us consider a dimensionless quantity $\Delta\nu$ defined by

$$\Delta\nu=\frac{\lambda-\lambda_0}{\lambda_0}=\frac{\Delta n}{n_0}+\frac{\Delta L}{L_0}-\frac{\Delta m}{m_0}, \qquad (6)$$

Table I. Measured values of $\Delta\nu$ corrected for the obliquity angle θ.

Obliquity angle θ (mrad)	Gauge blocks	
	75-mm	200-mm
1.23	—	-2.4×10^{-8}
0.91	—	$+0.4\times10^{-8}$
0.58	-9.9×10^{-8}	-3.2×10^{-8}

where Δn is the deviation of the measured refractive index from n_0, ΔL the change of length of a gauge block by temperature change, and Δm the fractional part of the order of interference obtained by the experiment.

The mean values of experimental results of $\Delta\nu$ are shown in Table I. Each value is corrected for the obliquity angle θ. The number of repeats of each measurement was fifteen. The standard deviations of measured values are 1.2×10^{-7} with the 75-mm gauge block and 5×10^{-8} with the 200-mm gauge block. Since the length $(=L_0)$ of each gauge block was measured with standard deviations of 0.009 μm with the 75-mm block and 0.012 μm with the 200-mm block using the gauge block interferometer in the visible region, the standard deviations are almost the same in the visible and in the infrared regions. The accuracy of the measurement is mainly dependent on the measurement of temperature for lengths greater than 100 mm.

§4. Discussion

At present, the lengths of gauge blocks longer than several tens of centimeters have been determined by sequences of measurements because the natural light in the visible spectrum is used. However, standard gauge blocks are known simply within an error of about 1 μm in length by another measurement. Therefore, the 3.39 μm He–Ne laser interferometer can measure absolute lengths in one step and automatically because of the coherent and long-wavelength radiation of the infrared laser, so that it is excellent in efficiency.

If the 3.39 μm He–Ne laser and the 0.633 μm He–Ne laser, which are stabilized at present, are used in this interferometer (their wavelength ratio equals 5.3), the excess fraction method can be achieved using these two wavelengths. The length that may be determined is the one whose deviation from a length known by another method is within about 5 μm.

The phase shift of interference fringe due to diffraction is about 5×10^{-8} for an aperture of 8.0 mm in diameter and a length 1m at 3.39 μm.[10,11] For obtaining the true wavelength, measured values must be corrected by this value.

With the enlarging obliquity angle in the interferometer, the accuracy of correction for the cosine error becomes worse. Therefore, it is not desirable to make θ large. In this experiment, the obliquity angle of 0.6 mrad eliminated the back-talk effect and the accuracy of correction is about 3×10^{-8} because of the alignment error of $\pm$0.05 mrad.[12] If the isolator for eliminating the back-talk effect is used, the alignment error is almost negligible.

§5. Conclusion

The 3.39 μm laser interferometer was described for length measurement. Using this interferometer, the length of the gauge block of nominal length 200 mm was determined with an accuracy in the order of 10^{-8}. The refractive index of air was measured with an accuracy of 3×10^{-8} at a wavelength of 3.39 μm.

This interferometer is of excellent accuracy and efficiency. The interferometry in the infrared is superior to that in the visible region for measuring a long distance.

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