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Differential laser-interferometer for thermal expansion measurements

KOJI MASUDA,[1,*] DAVE ERSKINE,[2] AND ORSON L. ANDERSON[3]

[1]Geological Survey of Japan, Tsukuba 305-8567, Japan
[2]Lawrence Livermore National Laboratory, Livermore, California 94551, U.S.A.
[3]University of California, Los Angeles, Los Angeles, California 90095, U.S.A.

ABSTRACT

The differential laser interferometry method and its application for measuring the thermal expansion of samples is described. The thermal expansion of single-crystal Al_2O_3 (corundum) was measured up to 1000 K with the differential laser-interferometer. The changes in the distance between two faces of a stepped shape sample are measured. The main feature of the apparatus is simultaneously monitoring two fringe signals that are 90° out of phase. This improvement of the basic laser-interferometer allows us to remotely measure the thermal expansion of minerals with high precision. The overall sensitivity with which we can detect changes in length is about 1/100 of the wavelength of the He-Ne laser (1/100 of 0.6328×10^{-6} m). After adjusting for errors caused by heat, the thermal expansion data measured with the differential laser-interferometer are in good agreement with previous reports. Use of this apparatus allows the investigation of the high-temperature thermodynamic properties of important rock-forming minerals.

INTRODUCTION

Thermal expansion data of the minerals that are stable in the Earth's interior are very important in equations of state, and in thermodynamics applied to geophysical problems. The coefficient of the thermal expansivity, α, temperature derivative of thermal expansion, often appears as a multiplying factor of the several elastic constants so that the limitation of the application is controlled by the accuracy of α at high temperatures (Anderson 1991; Anderson and Isaak 1995). Values of α at the temperature higher than 1200 K are generally estimated based on extrapolation of data taken up to about 1200 K (Wachtman et al. 1962; Suzuki et al. 1979; Anderson et al. 1992). Various experimental measurements of α often diverge at the temperature range higher than around 1000 K as shown by Anderson (1991). Precise data of thermal expansion would allow tighter constraints on thermodynamic approach toward clarifying the equation of state of the earth's interior. Contact techniques are not feasible above 1000 K due to apparatus distortion. A non-contact technique such as an optical technique will possibly provide the requisite accuracy.

The fundamental laser interferometer technique provides an accuracy of the order of the wavelength of light if we use only fringe counting to measure the change in beam path difference. Matsui and Manghnani (1985) measured the thermal expansion of single-crystal forsterite to 1023 K by Fizeau interferometry. Basically they use the fringe counting to measure the thermal expansion and their samples are in contact with other material. Fizeau interferometry methods are limited to temperature below about 1110 K by practical considerations. The 90° phase shift technique has been used to improve the accuracy of the laser interferometry. However the beam paths are often complicated (Roberts 1975) and the optical layout has problems caused by the table dilation (Miiller and Cezairliyan 1991). We made a new version of the differential laser interferometer which uses the 90° phase shift technique. The advantages of our apparatus are simplicity of optical layout, which shortens path length difference, and decouples table thermal expansion from the data.

This report describes a differential laser interferometry method and its application to remote measurements of the thermal expansion of the step-shape crystals at high temperatures under the atmospheric pressure. To demonstrate the accuracy, we measured the changes in the length of the standard material of single-crystal Al_2O_3 (corundum) up to 1000 K, in which range the thermal expansion has been accurately measured by many groups.

EXPERIMENTAL METHODS

Differential laser-interferometer

Differential laser interferometry is similar to the method described by Hemsing (1979) for velocity interferometers. The basic laser interferometer is modified to maximize sensitivity by simultaneously monitoring the two fringe signals that are 90° out of phase. We added a $\lambda/8$ retardation plate (birefringent waveplate) and a polarizing beamsplitter to the basic laser interferometer optics. Figure 1 is a schematic.

We used the He-Ne laser of which light was polarized by a polarizer at 45° to the horizontal so that equal intensities were applied to vertical and horizontal polarization states. The laser

*E-mail: masuda@gsj.go.jp

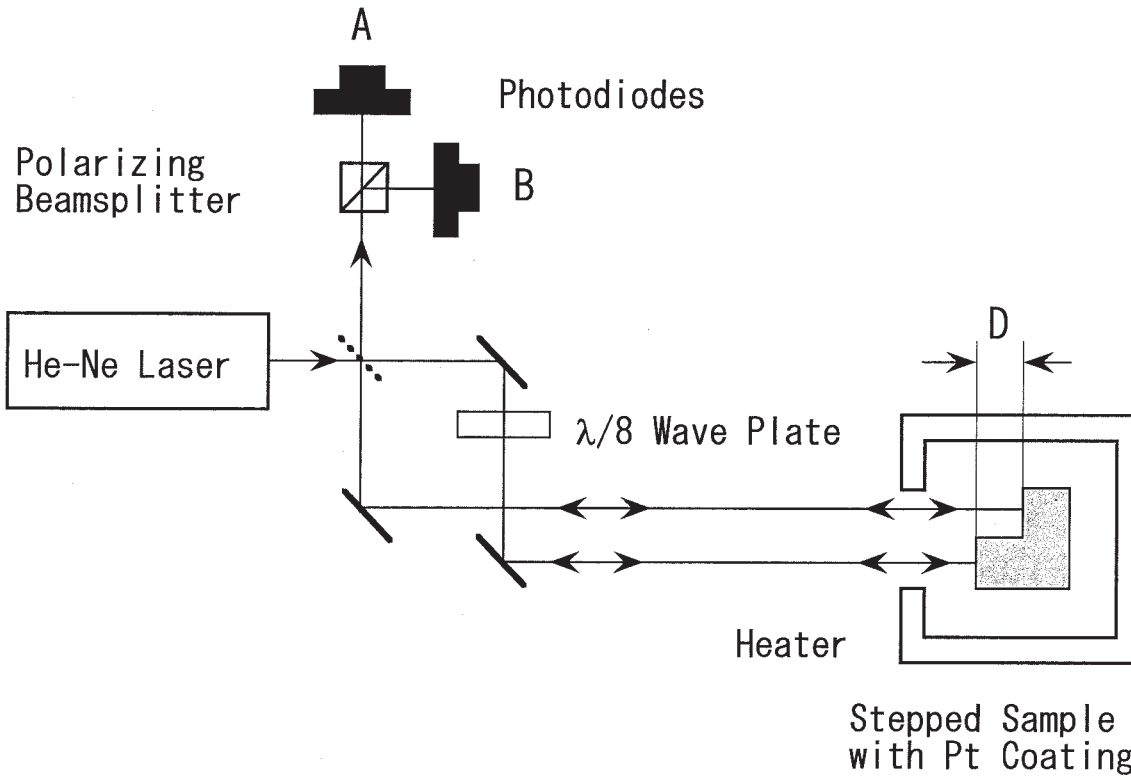

FIGURE 1. The principle of the differential laser-interferometer. The basic laser interferometer is modified to maximize sensitivity by simultaneously monitoring the two fringe signals that are 90° out of phase. The λ/8 wave plate is arranged to introduce a 90° phase difference between the horizontal component and the vertical component of the laser bean. Photodiode A and B measure the intensities of the horizontal compenent and the vertical component of fringe patterns. The sample is stepped by D.

was not stabilized on a single mode. Because we used many longitudinal modes, the average frequency over those longitudinal modes is fairly stable. The laser was not amplitude stabilized. This is unneccessary because the data analysis algorithm normalizes the data to the amplitude. The laser was not frequency stabilized but an unstabilized laser is sufficient here because the spacing of modes of the interferometer are broader than the spacing of modes in He-Ne laser, and because the interferometer path length difference is 10 mm whereas the laser cavity roundtrip length is 600 mm.

The λ/8 waveplate is arranged to introduce a 90° phase difference between the horizontal and the vertical polalizations of one of the divided beams traveling through the interferometer optics. The λ/8 waveplate induces a 45° phase lag between horizontal and vertical fringe phases. The light travels twice through the λ/8 waveplate thus when recombination occurs at the beam splitter, the horizontally and vertically polarized components form two fringe patterns that are 90° out of phase. The two patterns are separated from each other by the polarizing beam splitter and then sent to two photodiodes. Photodiode A measures the intensity of the horizontal component of fringe pattern, while photodiode B measures the vertical component.

Sample shape

A stepped shape sample is used in this technique. We cut a single crystal of corundum into a cube with dimensions of 10 mm. The sample was then stepped by 5 mm, *D*, so that light is reflected off two faces of the same sample, thus eliminating any possible effects due to subtle motion of the sample itself. When two parallel beams travel between the interferometer and the sample, translational movement of the sample relative to the interferometer, such as caused by oven movement, does not change *D* because it affects both arms equally. The sample was coated with platinum to obtain a high reflectivity at high temperatures.

Fringe signal analysis

Figure 2 schematically illustrates the output signals of the differential interferometer. The signal A represents the horizontal component of the fringe intensity and the signal B represents the vertical component. As the length *D* of the sample increases due to thermal expansion, the output signals A and B show fringe patterns which are 90° out of phase. The outputs of each of the photodiodes are used as inputs for an X-Y display similar to the display of a Lissajous figure. Each fringe traces out one Lissajous figure on the scope. The passage of one fringe corresponds to the change in *D* by λ/2, with λ being the wavelength of the laser beam used.

The change in angle Ω of Lissajous figure can be easily measured with extreme precision. The optical path difference of the two interferometer beams is 10 mm, twice the sample step size. The stability of average wavelength of our laser is on the order of 1×10^{-6}. Observed scatter in the angle Ω vs. tem-

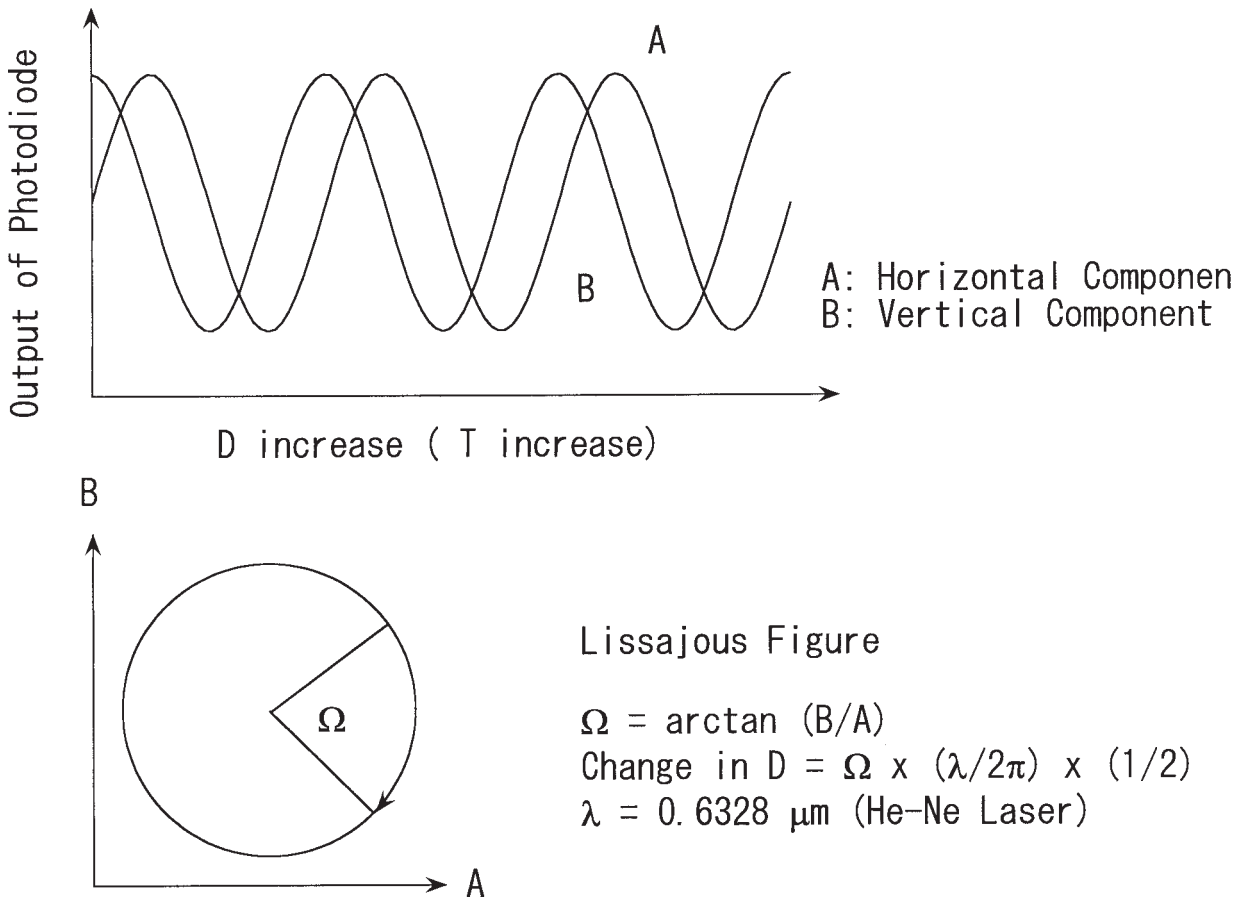

FIGURE 2. Schematic drawings of outputs from two photodiodes and Lissajous figure. Trace A shows the intensity of the horizontal component of fringe pattern, and B shows the vertical component. These two traces are 90° out of phase. When these traces are plotted against each other (x-y mode), the Lissajous figure in result. The trace of one Lissajous figure corresponds to the change in the length D of $\lambda/2$. λ is the wavelength of He-Ne laser.

perature was about 4°. The detection sensitivity can reach nearly 1/100 of a wavelength of the laser beam. This method has been proven reliable for measuring changes in length to a fraction of the He-Ne laser light; that is on the order of 600 nm.

Data correction

We can determine the increase in the sample step length D by analyzing the phase of Lissajous Ω,

$$\Omega = 2\pi(2\,nD\,/\lambda) + \text{constant}. \quad (1)$$

Instead of measuring sample step distance D, we are actually measuring $n(T)D$, where $n(T)$ is the temperature dependent refractive index of air and $n = 1.0002922$ for air at 273 K, 1 atm, and the He-Ne light, and where λ is the wavelength of the He-Ne laser beam. Increasing temperature caused a decrease in n, which mimics a shrinking sample (of fractional change 2.045×10^{-4} at 1000 K). Thus actual sample growth values will be greater than measured. The fractional sample growth is

$$\Delta D/D_0 = \lambda\Delta\Omega/4\pi nD_0 - \Delta n/n. \quad (2)$$

We can approximate n to be unity and obtain a working equation for air correction heated from 300 K,

$$\Delta D/D_0 = \lambda\Delta\Omega/4\pi D_0 + 2.922 \times 10^{-4}\,(1 - 300/T). \quad (3)$$

Care must be exercised so that the change in path length measured is due to the sample and not to the change in the distance between interferometer optics. Heating of the oven can cause the table to expand. If one interferometer arm expands more than the other, a false sample growth will appear. We performed null experiments by measuring the distance change when both laser beams reflect off the same face as the sample is heated. Any fringe shift in this arrangement is entirely due to thermally induced path length change in the distance between the optics. We subtract the observed thermal induced path length change from the measured data.

RESULTS AND DISCUSSION

We measured the thermal expansion of single-crystal corundum in order to demonstrate our technique. A single crystal of Al_2O_3 was cut into cubic shape along the crystal c axis then stepped by D. The original length of sample step, D_0, was 4.955 mm. We measured the change in the length D with our differ-

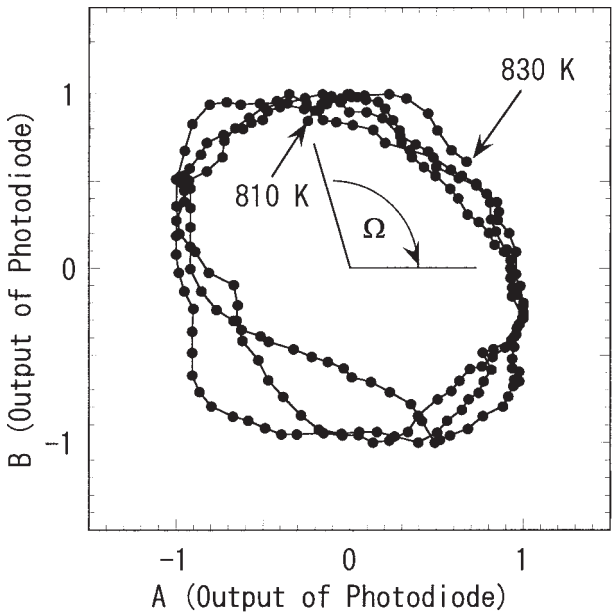

FIGURE 3. Sample Lissajous figure formed from the outputs of two photodiodes A and B in the temperature range from 810 K to 830 K.

ential interferometry technique. Figure 3 shows the Lissajous figure corresponding to the signals in the temperature range from 810 K to 830 K. As the temperature increases, the data point moved clockwise. The intensity of the output signals from the photodiodes is normalized into the range from –1.0 to +1.0. From the change in angle Ω of Lissajous figure, we calculated the change in the length of sample step, ΔD.

Figure 4 shows the thermal expansion data, $\Delta D/D_0$, along the *c* axis of an Al_2O_3 single crystal measured from room temperature to 1000 K using our technique. Figure 4 shows the data with corrections for thermally induced path length and the temperature-dependent air refractive index. After adjusting the thermal expansion data as described above, measurements with the differential laser interferometer are in good agreement with the data reported by Watchman et al. (1962) and White and Roberts (1983) at all temperatures. The maximum error in the reported values of thermal expansion is estimated to be about 0.5% in measured temperature range. We use the similar analysis of errors arising from the measurement of specimen temperature, fringe count, and specimen length at room temperature carried out by Miiller and Cezailiyan (1982).

These measurements were limited partly by the capability of the heater. A heater capable of attaining higher temperature would expand the range of measurement. The precise thermal expansion data measured with this apparatus will contribute the investigation of the high-temperature thermodynamics of important rock-forming minerals.

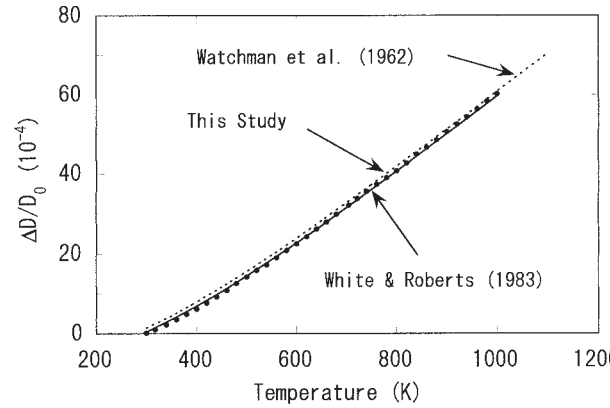

FIGURE 4. Thermal expansion of single-crystal Al_2O_3 in the direction of the *c* axis with corrections for thermally induced path length and air index. D_0 is 4.955 mm. Closed circles represent the data of the present study. Solid and dotted lines indicate the reported data by White and Roberts (1983) and Watchman et al. (1962).

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