Using a Michelson Interferometer to Measure Coefficient of Thermal Expansion of Copper

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When most materials are heated they expand.[1] This concept is usually demonstrated using some type of mechanical measurement of the linear expansion of a metal rod.[2] We have developed an alternative laboratory method for measuring thermal expansion by using a Michelson interferometer. Using the method presented, interference, interferometry, and the principle of thermal expansion can be taught concurrently. The material is accessible to undergraduates and advanced high school physics students.

In a Michelson interferometer (Fig. 1), collimated light is directed at a beam splitter. The resultant two beams of equal amplitude are reflected by mirrors approximately equidistant from the beam splitter. These two beams recombine at the beam splitter, where they interfere.[3] Optical interference occurs when the optical wave fields either cancel or reinforce. The interference pattern consists of either circular or parallel fringes (Fig. 2), depending on the orientation of the beams.[4] Figure 2 shows the actual interference fringes observed during the experiment. They were expanded with a lens, projected onto a screen, and then photographed with a digital camera. Destructive interference (cancellation) takes place at the dark fringes while constructive interference (reinforcement) takes place at the bright fringes. Alternate dark or bright fringes correspond to a phase difference of 2π. This, in turn, corresponds to a one-wavelength difference in path length between the two arms of the interferometer. When one of the mirrors is moved in the direction of the beam it reflects, the path length changes and the image shows a shift in interference fringes.

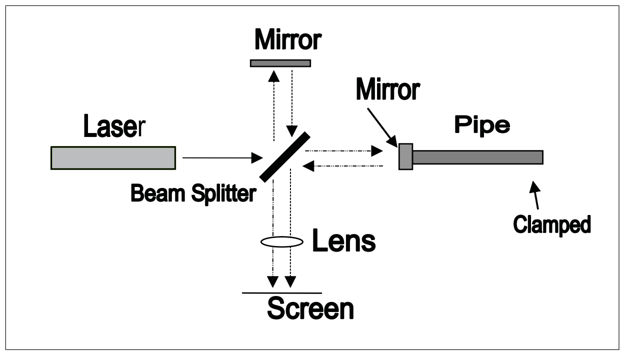

Fig. 1. Block diagram of the experimental setup (not to scale).

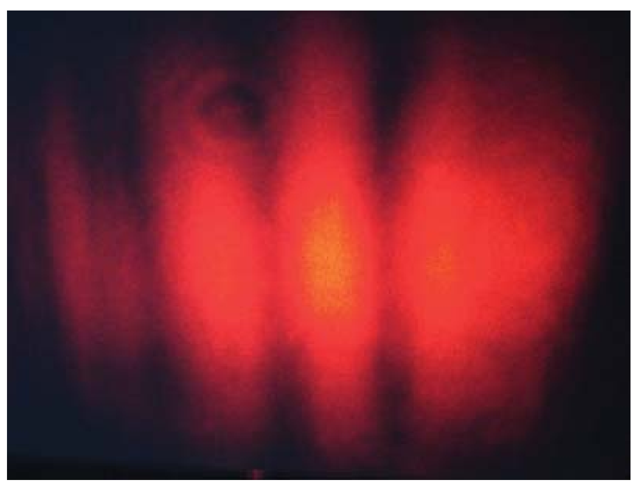

Fig. 2. Interference fringes obtained with the Michelson interferometer.

The linear expansion of copper is typically expressed as a constant given by α,[1,5]

$$\alpha = \frac{\Delta L}{L_0 \Delta T}, \quad (1)$$

such that L_0 is the initial length (prior to heating), ΔT is the change in temperature, and ΔL is the change in length. The change in length can be expressed as a number of wavelengths

$$\Delta L = \frac{n\lambda}{2}, \quad (2)$$

where n is the number of fringe shifts and λ is the wavelength of the laser light. A factor of 2 resides in the denominator because when the mirror moves a distance x, the path length changes by a distance $2x$. Combining Eqs. (1) and (2), we get

$$\alpha = \frac{n\lambda}{2L_0 \Delta T}. \quad (3)$$

Thus, the linear coefficient of thermal expansion α can be calculated from just a few measurable variables: the wavelength of the laser light, the number of fringe shifts, the initial pipe length, and the change in temperature.

In this experiment, the moving mirror of the Michelson interferometer is attached to a ¾-in copper pipe with Super Glue. The pipe was parallel with the beam so as the copper expands the mirror will move in the direction of the beam. This free end was supported by a loop of thick copper wire that had minimal contact with the pipe held by an optical mount. No effects due to friction were observed. The other end of the pipe was clamped (Fig. 3). The total length of the pipe was 59.7 cm, but for purposes of calculation the length 59.3 cm was used; that was the distance from the clamped position to the free end. As the pipe heats, it expands, changing the path length difference between the two arms. As the path length changes, the dark fringes become bright fringes and then dark again, corresponding to the changing phase. Every time a dark fringe conducts one such cycle, the path length has changed a single wavelength (in our case, 612 nm produced by an "orange" He-Ne laser). By counting these fringe shifts (number of fringes that seem to move), one can accurately determine the change in length of the pipe.

We chose copper because of its high coefficient of thermal expansion, availability, and low cost. To heat the pipe we placed an Amptek silicone heat tape inside of the pipe. We measured the pipe temperature with two thermocouple thermometers to within 1°C. They were affixed to the pipe 10 cm from each end with aluminum tape (which remains adhesive under heat). Foam pipe insulation was placed around the pipe to ensure uniform heating.

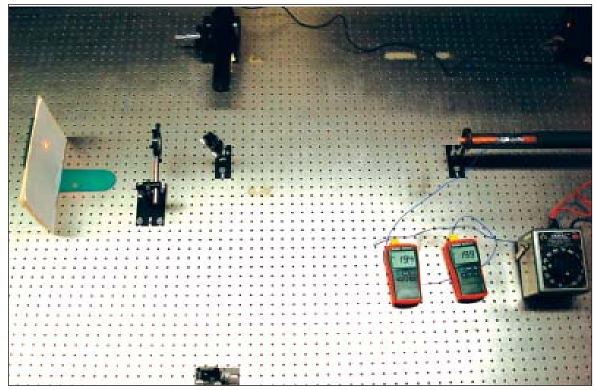

Fig. 3. Experimental arrangement.

The heat tape can warm the pipe quickly, faster than can be measured by the eye. To raise the temperature incrementally, we used a variable ac power supply (the Amptek tape normally operates at 120 V ac). Images of the fringes were recorded during the data runs using a modest built-in video camera on an Apple MacBook laptop computer, allowing us to recheck the number of fringe shifts using the Apple QuickTime program.

Since the Michelson interferometer is quite sensitive, only small temperature changes are needed. For example, from 26.9°C to 37.2°C, we observed 336 fringe shifts, obtaining the value $\alpha = 16.8 \times 10^{-6}$/°C. From 95.3°C to 105.8°C, we observed 358 fringe shifts, obtaining the value $\alpha = 17.7 \times 10^{-6}$/°C. Standard values are 16.5×10^{-6}/°C and 17.6×10^{-6}/°C at 20°C and 123°C, respectively.[7] For the range from 26.9°C to 105.8°C, we observed 2642 fringe shifts; the experiment yielded a value of $\alpha = (17.3 \pm 0.3) \times 10^{-6}$/°C. This is comparable to the usual value presented in textbooks of $\alpha = 17 \times 10^{-6}$/°C.

This Michelson interferometer can be assembled in about an hour. It is important to take care that the recombined beams are collinear, otherwise poor quality or no fringes will be produced. Reducing vibrations is also helpful. Figure 3 shows a digital photo of the experimental setup.

We have demonstrated an accurate method for measuring the coefficient of linear thermal expansion using a Michelson interferometer. Our method allows for the concurrent teaching of interference and interferometers as well. The students can actually see the changes to the fringe pattern as the pipe expands.

References

1. R.A. Serway and J.W. Jewett, *Physics for Scientists and Engineers,* 6th ed. (Thomson, Belmont, CA, 2004), p. 587.
2. See http://class.phys.psu.edu/213labs/ and click on "Thermal Expansion" in the left column to download the procedure for a laboratory experiment to measure thermal expansion by mechanical means.
3. Ref. 1, p. 1194.
4. E. Hecht, *Optics,* 4th ed. (Addison-Wesley, San Francisco, 2002), pp. 407-410.
5. While α actually varies with temperature, it remains essentially constant for minor temperature changes.
6. *CRC Handbook of Chemistry and Physics*, 86th ed., edited by D.R. Lide (Taylor & Francis, Boca Raton, 2005), pp. 12-196.
7. *Thermophysical Properties of Matter*, *Volume 12. Thermal Expansion, Metallic Elements and Alloys*, edited by Y.S. Touloukian (IFI/Plenum, New York, 1975), p. 76.

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