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THE MEASUREMENT OF SMALL MAGNETOSTRICTIVE EFFECTS BY AN INTERFEROMETRIC METHOD

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A new method is developed to measure small magnetostrictive effects. It is based on the assumption that the thermal expansion of a material is independent of its magnetization. Using ac modulation of the magnetic field, a stabilized Michelson interferometer detects the small vibrational amplitudes caused by the magnetostriction. A sensitivity to strictions $\Delta l/l$ as small as 5×10^{-11} is obtained. Results of striction measurements on bismuth are presented.

1. Introduction

In ferromagnetic, ferrimagnetic, and antiferromagnetic materials magnetostriction is, in general, a relatively large effect that is readily observed in magnetic fields of 1–2 T using standard measuring techniques such as strain gauges. In dia- and paramagnetic materials, however, this effect is considerably smaller. For the study of magnetic materials, the relation between the striction $\lambda^M (= \Delta l/l)$ of a material and its magnetization M is of considerable interest. Unfortunately, the measurement of this effect is, in general, hindered by the fact that the thermal expansion λ^T is of the same magnitude or even considerably higher than the value of the magnetostriction. A straightforward measurement of the dimensions of the sample thus gives a striction $\lambda = \lambda^M + \lambda^T$.

This problem, posed by the influence of the temperature, was first solved by Kapitza in 1931 [1]. He used a large field of 30 T to increase the value of λ^M resulting from the quadratic magnetostrictive effect in diamagnetic substances. Furthermore, he applied this field for a fraction of a second only, thus preventing λ^T from becoming comparable to λ^M.

Other solutions using the same approach, i.e., increasing λ^M and decreasing λ^T, have been given in 1934 by Wolf and Goetz [2], who repeated and extended the experiments of Kapitza with long samples and moderate fields, and by Fawcett [3] in 1970, who performed the measurements at cryogenic temperatures and large fields with a capacitance dilatometer.

2. Basic approach

We take a different approach to the problem by assuming that λ^T is independent of M, i.e. $d\lambda^T/dM = 0$, leading to $d\lambda/dM = d\lambda^M/dM$ which, as we will show, can be measured with the required accuracy and sensitivity, not only in the fields usually encountered, but also at room temperature. It can, using integrating methods, lead to the determination of λ^M as a function of M. For this purpose, we use an electromagnet equipped with modulating coils. By so doing, an ac field of suitable frequency H_1 can be superimposed on the dc field H_0 of the electromagnet. Apart from the striction λ_0 due to the dc field H_0, the sample will exhibit a striction λ_1 resulting from the ac field H_1. We must now fulfill two requirements. First, the value of H_1 must be small compared to H_0, and secondly, the frequency of the modulating field must be suitably chosen. Under these restrictions we may identify λ_1 with $d\lambda$ and H_1 with dH, so that

$$d\lambda/dH = \lambda_1/H_1 \,. \qquad (1)$$

In the case of dia- or paramagnetic materials we may, in general, write $d\lambda/dH = \chi d\lambda/dM$. With ferromagnetic materials, this conversion must include the dependence of χ on shape and direction of the sample. Integrating this quantity gives

$$\lambda^{M} = (1/\chi) \int_{M_1}^{M_2} (\lambda_1/H_1)\, dM . \tag{2}$$

Taking M_1 as zero and M_2 as the maximum applied field, we find λ^M as a function of M. The quantity H_1 can easily be measured with the required accuracy. For the measurement of the quantity λ_1, we use a stabilized Michelson interferometer, with which the measurement of vibrational amplitudes as small as 8×10^{-14}m has already been reported [4,5]. This sensitivity will be seen to be adequate for the measurement of the magnetostriction of dia- and paramagnetic materials in the fields usually encountered. Its application to the measurement of magnetostriction poses two problems.

First, the sample must be positioned on a support in the airgap of an electromagnet. This support will also have a magnetostrictive effect. Precautions must be taken to prevent the magnetostriction of the support from being measured as well. Secondly, the vibration of the electromagnet due to the Lorentz force on the current through the modulating coils may lead to misinterpretation of the measured signals. The solutions of these problems are obtained by modification of the optical system in the interferometer. This involves a new concept of the electromechanical transducer required in such an interferometer for the stabilization of the interference pattern.

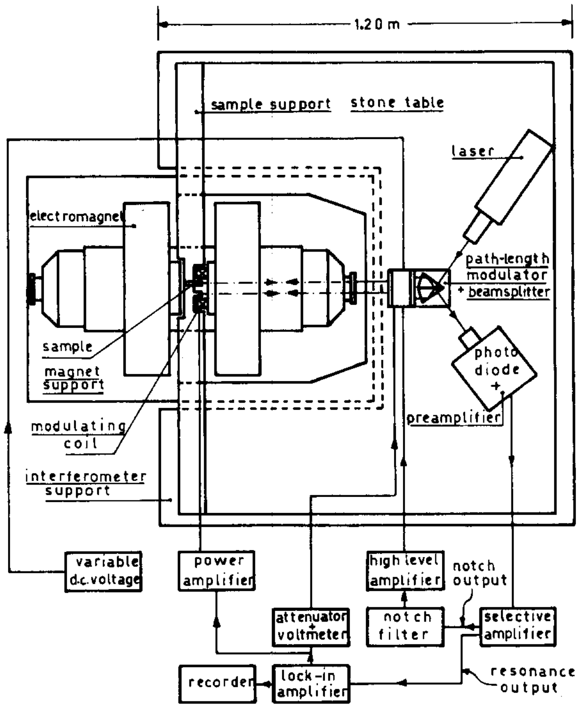

Fig. 1. Configuration of the interferometer for the measurement of magnetostriction and its electronic circuit.

3. Measuring set-up

The overall view of the measurement set-up is shown in fig. 1, while the details of the path-length modulator are shown in fig. 2.

The optical system is a modified Michelson interferometer. The light beam of a helium–neon laser is filtered by a spatial filter (lens–pinhole–lens combination) and passed through a Kösters prism. There it is divided into two parallel beams of equal intensity. These two beams enter the optical path-length modulator that replaces the electromechanical transducer already mentioned [4]. It consists of four transducers, each equipped with a roof-top prism as shown in fig. 2. These prisms reflect the two beams which, upon emerging from the modulator, pass through an axial hole in the electromagnet onto two mirrors. One of these mirrors is glued to the sample, while the other is mounted on the sample support. The reflected beams return along the same path through the modulator to the beam-splitting surface in the Kösters prism where they are both split into equal parts, resulting in a superposition of two beams returning to the laser and a superposition of two beams directed to the photodiode that detects the resulting interference pattern.

As shown in fig. 1, the optical parts of the interferometer are positioned on a stone table, except for the two mirrors in the electromagnet airgap that are supported by a Perspex bar whose ends are fixed to the stone table. Because of the lack of space in the airgap of the electromagnet and the low elastic modulus of Perspex, the rigidity of this support is low. The assumption that the mirror on the sample exhibits the vibration of the sample is no longer valid because the support may also show part of the vibrations of the sample. By our arrangement of the optical system,

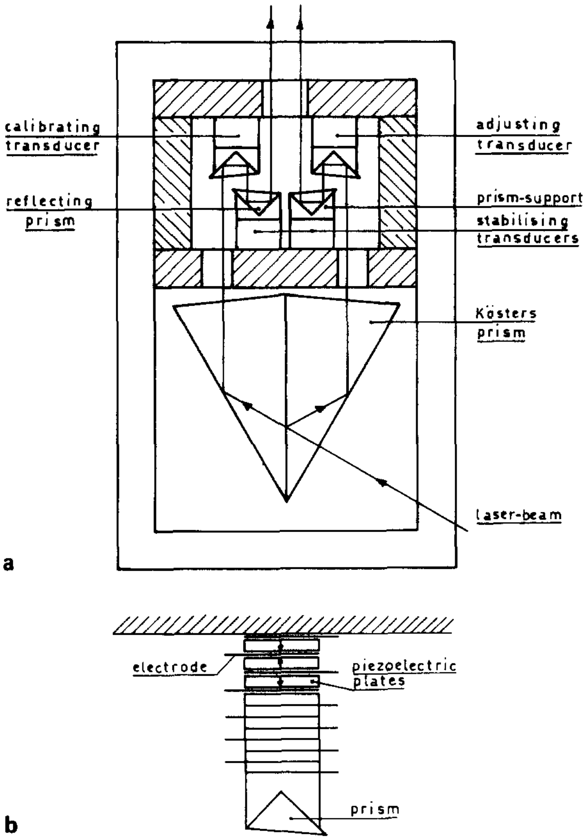

Fig. 2. (a) The path-length modulator and the Kösters prism. The shallow faces of the prisms prevent reflections at the air–glass interfaces from disturbing the interference pattern. (b) The arrangement of the piezoelectric plates in the electromechanical transducers. The arrows in the plates indicate the poling direction of the ceramic.

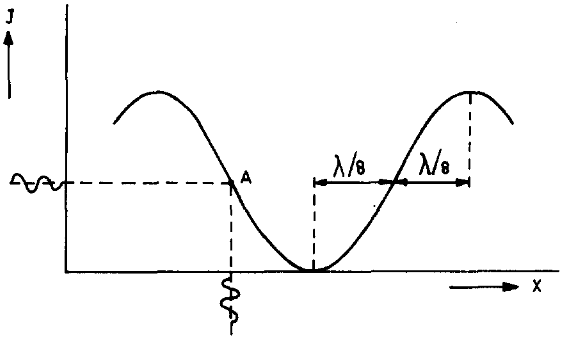

Fig. 3. The light intensity of the interference pattern as a function of the optical path-length difference. The mean light intensity on the photodiode must be kept at point A to obtain a constant and maximum sensitivity for path-length fluctuations.

however, we measure the effective vibration of the sample itself, because vibrations of the support now occur with equal amplitude and phase in both arms of the interferometer, thus not affecting the interference pattern. In the above-mentioned stabilized interferometer, one mirror is positioned on an electromechanical transducer, and is, in fact, the diaphragm of a condenser microphone. To place such an electromechanical transducer in the airgap of an electromagnet is very difficult because of the lack of space. It is undesirable because magnetic fields could affect the operation of such a transducer due to currents induced in its metallic parts. Hence, the optical path-length modulator was designed to replace the condenser microphone.

To explain the operation of the path-length modulator we should define the three functions combined in the microphone previously used. Its first function was to adjust the optimum working point (A in fig. 3) of the interference pattern by varying the mean bias voltage. The second was to keep the interferometer at this point by adding to the mean bias voltage a compensating voltage, proportional to the deviation of the light intensity from this point. The third was to feed an ac voltage with the frequency of the measuring signal to the microphone for calibration of the said signals. The three functions must be appropriately assigned to the four new electromechanical transducers. If we want to use piezoelectric ceramics, the main considerations are the difference in sensitivity between the condenser microphone (about 400 Å/V) and a piezoelectric plate (i.e. 3.6 Å/V for PZT 5) and the hysteresis effect exhibited by ferroelectric ceramics. A sensitivity of 3.6 Å/V is insufficient for the first two functions, as it requires a voltage swing in the order of 1000 V to cover the whole control range. To this end, we use as an electromechanical transducer a stack of ten piezoelectric plates, mechanically connected in series, and electrically in parallel. This leads to a tenfold increase in sensitivity at the expense of the useful frequency range which, however, still remains wide enough for our purposes. One of the four transducers is used to adjust the optimum working point on the interference pattern. It is driven by a dc voltage, adjustable between 0 and 200 V, thus covering about ten fringes of the interference pattern. Two transducers are used for stabilizing purposes, resulting in a sensitivity of 120 Å/V. To overcome the remaining difference in sensitivity, a high-level amplifier is incorporated in the feedback circuit. The last transducer, used for calibration of the measured signals, is itself calibrated once and for all with the aid of a condenser microphone [6]. It is used, with small ac voltages only to prevent hysteresis from affecting the calibration. Temperature and ageing have no noticeable influence on this calibration.

3.1. Electronic part

The electronic part of the measuring set-up is conventional in design (see fig. 1). The signal of the photodiode passes through a preamplifier to a selective amplifier. The notch output signal contains the information on the deviation of the mean light intensity of the interference pattern. The notch signal passes a second notch filter and the high-level amplifier that drives two of the transducers in the path-length modulator, thus stabilizing the interference pattern. The resonance output of the selective amplifier contains the ac signal resulting from the modulation of the striction by modulating the magnetic field. This signal is demodulated by a lock-in amplifier and recorded on paper strip. The reference signal of the lock-in amplifier is amplified by a power amplifier driving the modulating coils. The reference signal is used also for calibration. To this end we measure the amplitude of the fraction of the signal fed to the calibrated transducer. A well-defined path-length modulation is thus introduced, resulting in a signal on the recorder that can be compared with the signals from unknown path-length modulations caused by magnetostrictive effects. Attention must be paid to the fact than an amplitude of the calibrated transducer gives rise to a recorder signal twice as large as the signal resulting from the same amplitude of the vibrating sample. This is due to the fact that the light beam is reflected once by the sample and twice by the prism on the transducer.

4. Experiments and results

To illustrate the possibilities of the instrument, the measurement of the magnetostriction of a bismuth single crystal will be described and the results compared with those of Kapitza [1] and Wolf and Goetz [2].

From theory [1], the diamagnetic striction and the field strength are related by

$$\lambda_0 = \tfrac{1}{2} m H_0^2 , \tag{3}$$

m being a magnetostrictive parameter characteristic of the material. From eq. (3), it follows that

$$\mathrm{d}\lambda_0/\mathrm{d}H_0 = mH_0 . \tag{4}$$

As the amplitude of the applied modulating field is small compared to the magnetic field of the electromagnet, we use relation (1), so that

$$\lambda_1 = mH_0H_1 , \tag{5}$$

The bismuth samples used were three single crystals in the form of rods 10 mm in length and 6 mm in diameter. They were obtained from Highways International and had a purity specification of 5 N. The measurements were made in the direction of the rod axis, normal to the trigonal axis thus giving m_{33}. The measurement consisted in making a plot on a recorder of the striction λ_1 as a function of the field strength H_0 with a constant and suitable value of the modulating field H_1. The result was a perfectly straight line, at an angle arctan m to the H-axis (fig.

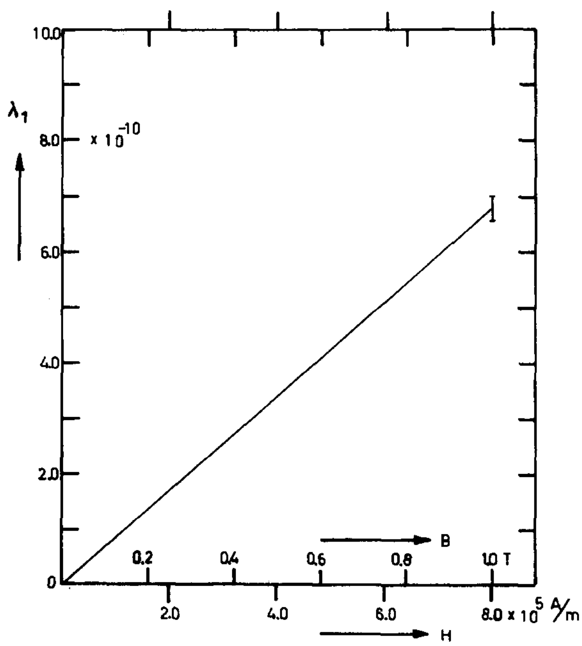

Fig. 4. Plot of the ac component of the striction λ_1 as a function of the dc magnetic field for bismuth. The length of the sample is 10.5 mm. The modulating field $H_1 = 9.3 \times 10^3$ A/m. The rms error is indicated by the small vertical line.

4). The H_0-axis was calibrated with a Hall-effect gaussmeter, while the λ_1 axis was calibrated with the aid of the calibrated transducer.

To examine the reproducibility of the measurements, we made five plots of one sample with different adjustments of the interference pattern. The result was a value of $\langle m_{33} \rangle = -91.6 \times 10^{-21}$ m^2 A^{-2}. The rms error determined from these five measurements is $\langle (m_{33} - \langle m_{33} \rangle)^2 \rangle^{1/2} = 1.7 \times 10^{-21}$ m^2 A^{-2}. Similar results were obtained with two other samples. For comparison, we mention the values found by Kapitza and Wolf and Goetz, that is $m_{33} = -101 \times 10^{-21}$ m^2 A^{-2} and $m_{33} = -90 \times 10^{-21}$ m^2 A^{-2}, respectively, at $T = 25°$C.

Our results agree very well with these figures. In comparison with Kapitza, our method has the advantage of being able to use ordinary fields and small samples. Additional advantages of our set-up are the electromechanical calibration, compared to Kapitza's thermal-expansion method, and the possibility of varying the modulating frequency and thus of examining the frequency response of the magnetostriction.

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References

[1] P. Kapitza, Proc. Roy. Soc. A131 (1931) 224; A 131 (1931) 243; A 135 (1931) 537; A 135 (1932) 556; A 135 (1932) 568.
[2] A. Wolf and A. Goetz, Phys. Rev. 46 (1934) 1095.
[3] E. Fawcett, Phys. Rev. B2 (1970) 1604.
E. Fawcett, Phys. Rev. B2 (1970) 3887.
[4] Th. Kwaaitaal, Rev. Sci. Instrum. 45 (1974) 39.
[5] W.M.J. Haesen and Th. Kwaaitaal, Rev. Sci. Instrum. 47 (1976) 434.