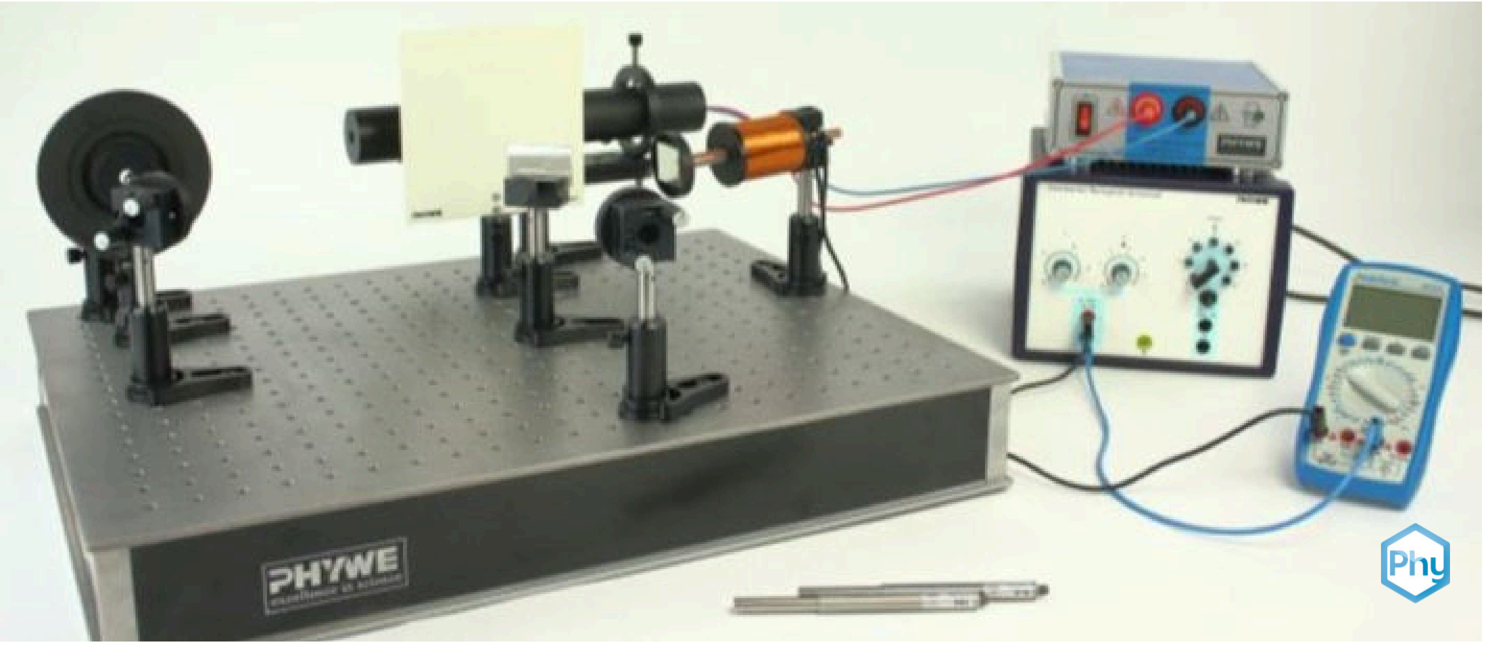
Magnetostriction with the Michelson interferometer



Physics | Light & Optics | Diffraction & interference

Difficulty level	Group size	Preparation time	Execution time
-	-	-	-

This content can also be found online at:

http://localhost:1337/c/5f3d880040ca6c000307b6f5

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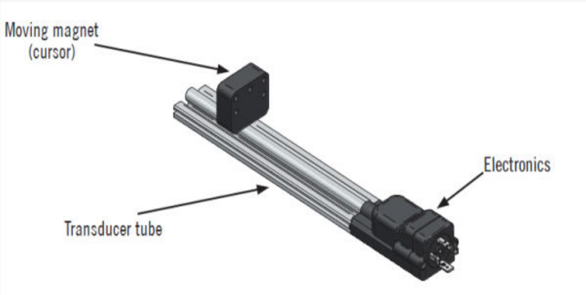
General information

Application



A magnetostrictive transducer

Magnetostriction is applied in:

- sensors: to measure a magnetic field or detect a force
- magnetostrictive transducers: to transfer ultrasonic energy into other material
- transformers: to convert magnetic fields into an electromotive force

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Other information (1/2)

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Prior knowledge

Interference occurs, when two light beams superpose to form a resultant wave of a greater, lower or same amplitude. The two waves must be coherent and emit the same wavelength.

Scientific principle

With the aid of two mirrors in a Michelson arrangement, light is brought to interference. Due to the magnetostrictive effect, one of the mirrors is shifted by variation in the magnetic field applied to a sample, and the change in the interference pattern is observed.

Other information (2/2)

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Learning objective

Understanding magnetostrictive properties of various materials (iron, nickel and copper) with Michelson interferometer.

Tasks

1. Construction of a Michelson interferometer using separate optical components.
2. Testing various ferromagnetic materials (iron and nickel) as well as a non-ferromagnetic material (copper) with regard to their magnetostrictive properties.

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Safety instructions

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For this experiment the general instructions for safe experimentation in science lessons apply.

For H- and P-phrases please consult the safety data sheet of the respective chemical.

The generally applicable rules for handling lasers according to the ANSI and IEC Laser Classification must be considered.

Do not see directly into the laser beam and reflected beam. Always wear the appropriate laser safety eyewears when the exit aperture of the laser is uncovered.

Theory (1/16)

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If two waves having the same frequency ω but different amplitudes and different phases are coincident at one location, they superimpose to

$$Y = a_1 \cdot sin(\omega t - \alpha_1) + a_2 \cdot sin(\omega t - \alpha_2)$$

The resulting wave can be described by the following:

$$Y = A \cdot sin(\omega t - \alpha)$$

with the amplitude

$$A_2 = a_1^2 + a_2^2 + 2a_1 a_2 \cdot cos\delta \quad (1)$$

and the phase difference

$$\delta = \alpha_1 - \alpha_2$$

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Theory (2/16)

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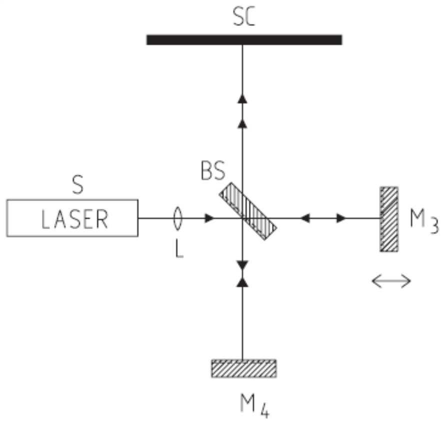
In a Michelson interferometer, the light beam is split by a halfsilvered glass plate into two partial beams (amplitude splitting), reflected by two mirrors, and again brought to interference behind the glass plate.

Since only large luminous spots can exhibit circular interference fringes, the light beam is expanded between the laser and the glass plate by a lens L.

If one replaces the real mirror M4 with its virtual image M4���,which is formed by reflection by the glass plate, a point P of the real light source appears as the points P' and P" of the virtual light sources L1 and L2.



Michelson arrangement for Interference. S represents the light source; SC the detector (or the position of the screen)

Theory (3/16)

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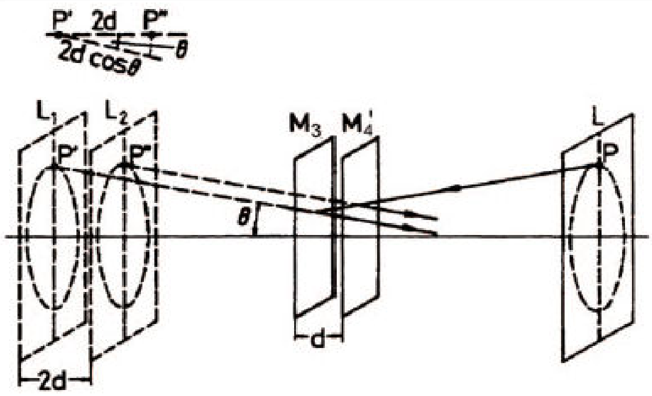
As a consequence of the different light paths traversed, and using the designations, the phase difference is given by:

$$\delta = \frac{\pi}{\lambda} \cdot 2 \cdot d \cdot cos\,\theta \qquad (2)$$

λ is the wavelength of the laser light used.

According to (1), the intensity distribution for $a_1 = a_2 = a$ is:

$$I \sim A^2 = 4 \cdot a^2 \cdot cos^2 \frac{\delta}{2} \qquad (3)$$



Formation of circular interference fringes

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Theory (4/16)

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Maxima thus occur when δ is equal to a multiple of \(2 \pi \) , hence with (2)

$$2d \cdot cos\,\theta = m\lambda \;\; ; \text{m = 1, 2, ...} \qquad (4)$$

i.e. there are circular fringes for selected, fixed values of *m*, and *d*, since θ remains constant.

If one alters the position of the movable mirror M3 such that *d*, e.g., decreases, according to (4), the circular fringe diameter would also diminish since mm is indeed defined for this ring. Thus, a ring disappears each time dd is reduced by $\lambda/2$.

For $d = 0$ the circular fringe pattern disappears. If the surfaces of mirrors M4 and M3 are not parallel, one obtains curved fringes, which gradually change into straight fringes at $d = 0$.

Theory (5/16)

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On magnetostriction:

Ferromagnetic substances undergo so-called magnetic distortions, i.e. they exhibit a lengthening or shortening parallel to the direction of magnetisation. Such changes are termed positive or negative magnetostriction.

The distortions are on the order of $\Delta l/l 10^{-8}$ to 10^{-4} n size. As is the case in crystal anisotropy, the magnetostriction is also ascribable to the spin-orbit mutual potential energy, as this is a function of the direction of magnetisation and the interatomic distances.

Due to magnetostriction, which corresponds to a spontaneous distortion of the lattice, a ferromagnet can reduce its total – anisotropic and elastic – energy.

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Theory (6/16)

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Inversely, in cases of elastic tension the direction of spontaneous magnetisation is influenced. According to the principle of the least constraint, this means the following: In cases of positive magnetostriction (in the case of iron (Fe)), under tensile stress the magnetisation is oriented parallel to the stress; in cases of compressive stress the magnetisation orients itself perpendicular to the pressure axis. In nickel (Ni) the situation is exactly reversed.

A true metal (ferromagnetic material) consists of small uniform microcrystals in dense packing, whose crystallographic axes are however irregularly distributed in all spatial directions.

The individual crystallites are additionally subdivided in Weiss molecular magnetic fields consisting of many molecules which form the elementary dipoles (*).

Theory (7/16)

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If the material has not been magnetised, all six (in nickel all eight) of the magnetic moment directions possible within a crystallite are present with equal frequency and consequently neutralise one another externally as a result of this irregular distribution. The magnetisation of the Weiss molecular magnetic fields is a function of temperature and occurs spontaneously below the Curie temperature .

However, as a consequence of the application of an external magnetic field this non-uniform distribution of the directions of magnetisation can be altered by the transition of a large number of Weiss molecular magnetic fields in the preferred light magnetisation directions, which have the smallest angle to the direction of the external magnetic field.

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Theory (8/16)

* On magnetic crystal anisotropy:

In monocrystals one observes a marked anisotropy of the magnetisation curve. This is due to the so called magnetic crystal energy. The source of this anisotropic energy in the transition metals (Fe, Ni and Co) is in their spin-orbit coupling energy, which is based on the relativistic interaction between spin and orbital movement.

In a rotation (directional alteration) of the spin, which is coupled by the mutual exchange energy, the orbital moments experience a torsional moment such that they also experience rotation. In an anisotropic electron distribution (d electrons) this effects a change in the overlapping of the electron clouds of adjacent atoms and hence an alteration of the total crystal energy.

One thus differentiates between the longitudinal magnetostriction, a length change parallel to the field direction and a transverse magnetostriction of the length alteration perpendicular to the external field direction.

Theory (9/16)

The relative length change $\lambda = \Delta l / l$ generally increases with increasing magnetisation and reaches a saturation value λ_s at $M = M_s$ (M_s : saturation magnetisation).

The relative volume change $\Delta V / V$ (i.e., volume magnetostriction) is usually considerably smaller, since longitudinal and transverse magnetostriction nearly always have opposite signs and compensate each other to a large extent.

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Theory (10/16)

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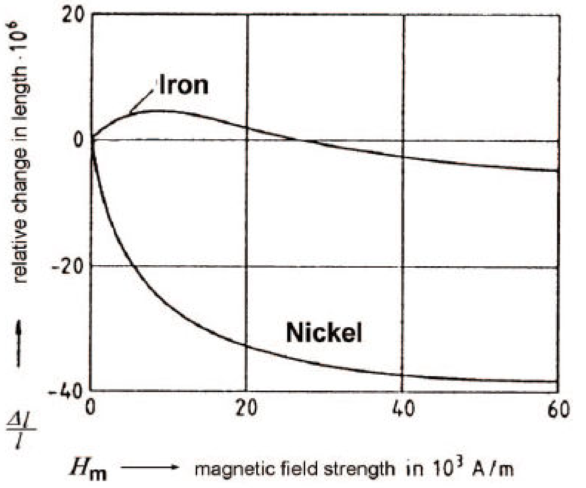

Magnetostriction of different ferromagnetic materials

In this experiment only the longitudinal magnetostriction is considered. One must take into consideration that the magnetostriction is a function of temperature and that premagnetisation is necessary.

Theory (11/16)

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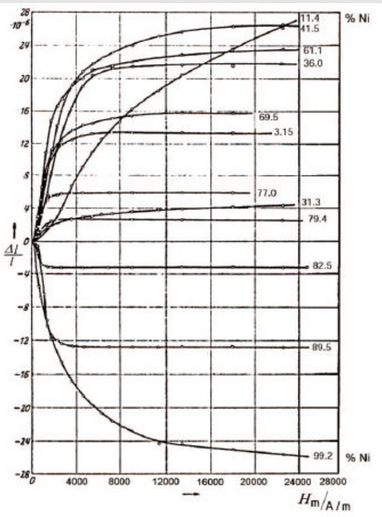

Magnetostriction of different ferromagnetic alloys

Additionally, the magnetostriction in alloys is also dependent on the composition of the metals and the appropriate pre-treatment.

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Theory (12/16)

Thermodynamic description of magnetostriction:

S : elastic tension

s : elastic deformation (i.e.: $\Delta l/l$)

B : magnetic induction

H : magnetic field strength

μ : magnetic permeability with $\frac{1}{\mu} = \frac{\partial H}{\partial B}$

E : Elasticity module with $E = \frac{\partial S}{\partial s}$

Theory (13/16)

As a result of thermodynamic relationships, it can be shown that the direct and reciprocal magnetostriction effects are mutually linked via

$$\frac{\partial S}{\partial B} = \frac{1}{4\pi} \cdot (\frac{\partial H}{\partial s}) \qquad (5)$$

For a free rod (unloaded and not clamped in position), the following is true:

$$s = -y\frac{B}{E} \qquad (6)$$

with the substance-specific quantity

$$y = \frac{\partial S}{\partial B}$$

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Theory (14/16)

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In other words, the relative longitudinal change is given by

$$s = -y\mu\frac{H}{E} \qquad (7)$$

In this context, *y* cannot be a constant as otherwise a linear increase in the relative length with the magnetic field strength would result. This is however not the case, since a saturation value is reached as of a specific field strength.

Theory (15/16)

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The magnetic field strength of a cylindrical coil is given by:

$$H_m = \frac{N.I}{\sqrt{4.r^2 + l_s^2}} \qquad (8)$$

where

H_m : magn. field strength at the centre of the coil in $A.m^{-1}$

r : Radius of a winding (here: 0.024 m)

l_s : Length of the coil (here: 0.06 m)

N : Number of windings (here: 1200)

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Theory (16/16)

On condition that the field is homogenous, the field strength is by the following for l >> r:

$$H = \frac{NI}{l} \qquad (9)$$

For this measurement we assume, as a first approximation, that the magnetic field strength H_m acts on the entire length of the rod (*l* = 0.15 ml).

The alteration in length Δl is obtained from the number of circular fringe changes *n*; in the process the separation per circular fringe change alters by $\lambda/2$ (λ = 632 nm):

$$\Delta l = n \cdot \lambda/2 \qquad (10)$$

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Equipment

Position	Material	Item No.	Quantity
1	Optical base plate 450 x 600 mm	08750-00	1
2	He-Ne Laser, 632 nm, 1 mW, linear polarised	08182-93	1
3	Adjusting support 35 x 35 mm	08711-00	3
4	Surface mirror 30 x 30 mm	08711-01	4
5	Accesory set for optical base plate	08750-50	1
6	Holder for diaphragms and beam splitters	08719-00	1
7	Beam splitter 1/1, non polarizing	08741-00	1
8	Lens, mounted, f +20 mm	08018-01	1
9	Lensholder for optical base plate	08723-00	1
10	Screen, white, 150x150 mm	09826-00	1
11	Faraday modulator for optical base plate	08733-00	1
12	Rods for magnetostriction,set	08733-01	1
13	PHYWE Power supply, universal DC: 0...18 V, 0...5 A / AC: 2/4/6/8/10/12/15 V, 5 A	13504-93	1
14	Digital multimeter, 600V AC/DC, 10A AC/DC, 20 MΩ, 200 µF, 20 kHz, −20°C… 760°C	07122-00	1
15	Connecting cord, 32 A, 500 mm, blue	07361-04	1
16	Magnetic foot for optical base plate	08710-00	1

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Setup and procedure

Setup (1/3)

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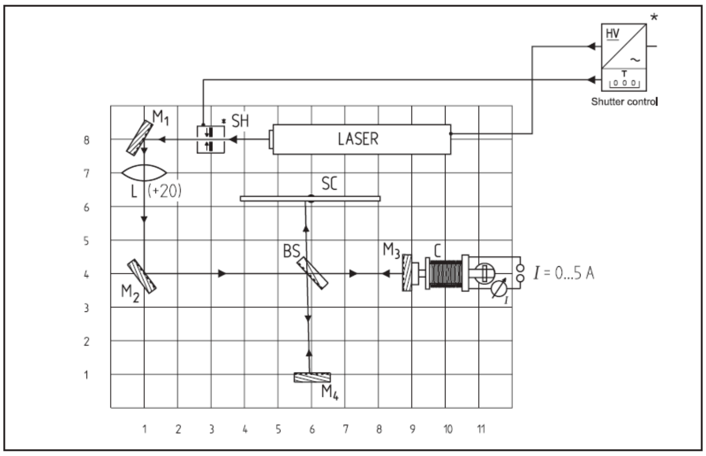

Experimental set-up (*only necessary with the 5-mW laser)

Perform the experimental set-up according to the figure. The recommended set-up height (beam path height) is 130 mm.

The lens **L** [1,7] must not be in position when making the initial adjustments.

When adjusting the beam path with the adjustable mirrors **M1** [1,8] and **M2** [1,4], the beam is set along the 4th *y* coordinate of the base plate.

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Setup (2/3)

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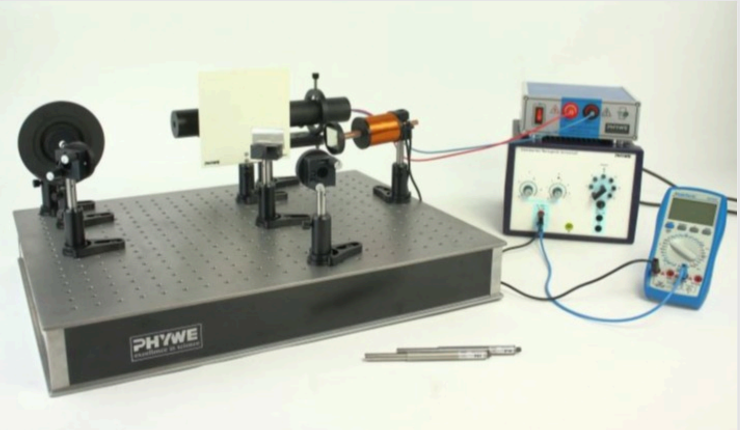

Experimental set-up

Place mirror **M3** onto the appropriate end of a sample (nickel or iron rod) – initially without the beam splitter – and screw it into place.

Now, insert the sample into the coil in such a manner that approximately the same length extends beyond the coil on both ends so that a uniform magnetisation can be assumed for the measurement. Fix the sample in position with the laterally attached knurled screw.

Next, insert the coil **C**'s shaft into a magnetic base and place it at position [11,4] such that the mirror's plane is perpendicular to the propagation direction of the laser's beam.

Setup (3/3)

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Adjust the beam in a manner such that the beam reflected by mirror **M3** once again coincides with its point of origin on mirror **M2**. This can be achieved by coarse shifting of the complete unit of coil with magnetic base or by turning the sample rod with mirror **M3** in the coil and by meticulously aligning mirror **M2** [1,4] with the aid of its fine adjustment mechanism.

Next, position the beam splitter **BS** [6, 4] in such a manner that one partial beam still reaches mirror **M3** without hindrance and the other partial beam strikes mirror **M4** [6, 1]. Die metallized side of **BS** is facing mirror **M4**.

Two luminous spots now appear on the screen **SC** [6, 6]. Make them coincide by adjusting the mirror **M4** until a slight flickering of the luminous spot can be seen.

After positioning lens **L** [1,7], an illuminated area with interference patterns appears on the screen. To obtain concentric circles, meticulously readjust mirror **M4** using the adjustment screws.

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Procedure (1/2)

Subsequent to the connection of the coil to the power supply (connect the multimeter in series between the coil and the power supply to measure the current, measuring range 10 AC!), set the DC-voltage to maximum and DC-current to minimum value. Then slowly readjust the current. For the measurements the resulting currents lie between 0.5 and, maximally, 5 A. Count the changes from maximum to maximum (or minimum to minimum) in the interference pattern.

In addition, pay attention to the direction in which the circular interference fringes move (sources or sinks!). Repeat this procedure using different samples and different current strengths I between 0.5 and 5.0 A (I > 3 A only for a short time!).

Calculate, for each measurement, the alteration length Δl using (10), relative length change $\Delta l / l$, and the magnetic field H using (9). 8. Plot a single graph of relative length change against the magnetic field strength for nickel and iron

Procedure (2/2)

Notes:
The materials require a certain amount of premagnetisation; therefore, the current should be run up and down several times for each individual determination before performing the intensity change measurement. The blank experiment with a copper rod as sample should serve to demonstrate that the longitudinal deformation effect is due to magnetostriction and not due to other causes.

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Evaluation (1/5)

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The results of the measurements on iron are summarised. In the measurements, the direction of magnetostriction also became apparent:

I/A	$H/\frac{A}{m}$	**Ring changes /** n	$\Delta l/10^{-6}m$	$\frac{\Delta l}{l}/10^{-6}$
0.83	16600	$\approx$ 11/4	0.395	2.630
1.27	25400	$\approx$ 13/4	0.554	3.691
1.60	25400	$\approx$ 11/2	0.475	3.164
1.87	37400	$\approx$ 11/4	0.395	2.630

$^{*}l = 0.15\,m$

Measurements of iron

Evaluation (2/5)

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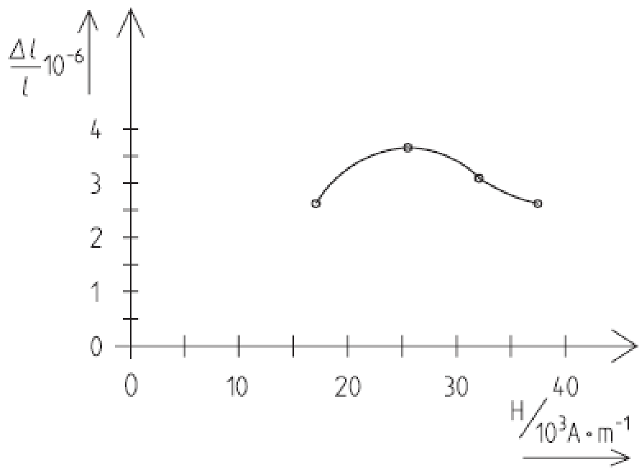

Results of the magnetostriction of iron

The relative change in length $\Delta l/l$ is plotted against applied field strength H

In iron, the radii of the interference rings increased with increasing magnetic field strength (sources!); thus, the rod must have become larger.

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Evaluation (3/5)

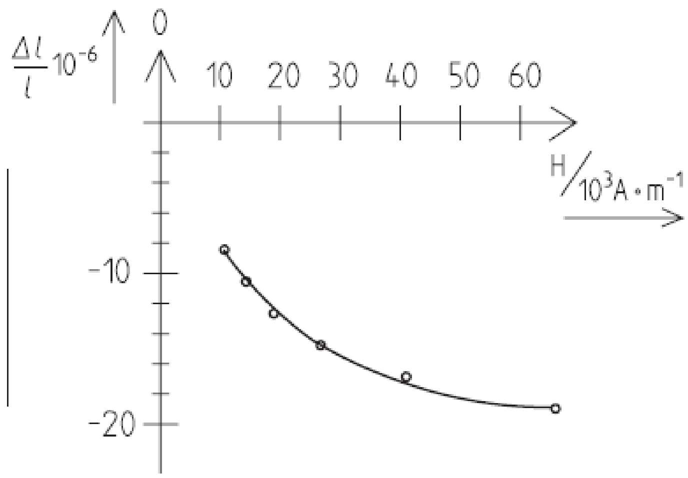
The results of the measurements on nickel are summarised.

I/A	$H/\frac{A}{m}$	Ring changes / n	$\Delta l/10^{-6}m$	$\frac{\Delta l}{l}/10^{-6}$
0.53	10600	4	-1.27	-8.44
0.71	14200	5	-1.58	-10.55
0.94	18800	6	-1.90	-12.67
1.33	26600	7	-2.21	-14.77
3.28	65600	9	-2.84	-18.98

$^*l = 0.15\,m$

Measurements of nickel

Evaluation (4/5)



Results of the magnetostriction of nickel

In nickel the rod became shorter (sink of circular interference fringes); therefore, a negative magnetostriction existed in this case.

The comparison with the literature values exhibited good agreement. In copper no alteration in length can be detected for a rapid current elevation. It may be possible that a slow heating of the material would show changes in the circular interference rings over a long period of time.

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Evaluation (5/5)

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Fill in the blank:

Magnetostriction is property of ______ materials that causes them to expand or ______ in response to ______ field. Such changes are termed positive or negative magnetostriction. Here ______ is subjected to positive magnetostriction, which means under tensile stress the magnetisation is oriented parallel to the stress and in cases of compressive stress the magnetisation orients itself perpendicular to the pressure axis. Whereas for ______, the situation is exactly reversed.

- nickel
- contract
- magnetic
- iron
- ferromagnetic

Check

Slide	Score / Total
Slide 33: Magnetostriction	**0/5**

Total Score 0/5

Show solutions   Retry

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