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GYROMAGNETIC MATERIALS INTENDED FOR APPLICATION AT MICROWAVE FREQUENCIES – MEASURING METHODS FOR PROPERTIES

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 60556 has been prepared by IEC technical committee 51: Magnetic components and ferrite materials.

This second edition cancels and replaces the first edition, published in 1982, its amendment 1 (1997) and amendment 2 (2004). This edition constitutes a technical revision.

This second edition is a consolidation of the first edition and its amendments 1 and 2. It includes editorial improvements as well as improvements to the figures.

This standard is to be read in conjunction with IEC 60392.

The text of this standard is based on the following documents:

FDIS	Report on voting
51/850/FDIS	51/859/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

GYROMAGNETIC MATERIALS INTENDED FOR APPLICATION AT MICROWAVE FREQUENCIES – MEASURING METHODS FOR PROPERTIES

1 Scope

This International Standard describes methods of measuring the properties used to specify polycrystalline microwave ferrites in accordance with IEC 60392 and for general use in ferrite technology. These measuring methods are intended for the investigation of materials, generally referred to as ferrites, for application at microwave frequencies.

Single crystals and thin films generally fall outside the scope of this standard.

NOTE 1 For the purposes of this standard, the words “ferrite” and “microwave” are used in a broad sense:

– by “ferrites” is meant not only magneto-dielectric chemical components having a spinel crystal structure, but also materials with garnet and hexagonal structures;

– the “microwave” region is taken to include wavelengths approximately between 1 m and 1 mm, the main interest being concentrated on the region 0,3 m to 10 mm.

NOTE 2 Examples of components employing microwave ferrites are non-reciprocal devices such as circulators, isolators and non-reciprocal phase-shifters. These constitute the major field of application, but the materials may be used in reciprocal devices as well, for example, modulators and (reciprocal) phase-shifters. Other applications include gyromagnetic filters, limiters and more sophisticated devices, such as parametric amplifiers.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendment) applies.

IEC 60050-221, *International Electrotechnical Vocabulary (IEV) – Part 221: Magnetic materials components*

IEC 60205:2006, *Calculation of the effective parameters of magnetic piece parts*

IEC 60392:1972, *Guide for the drafting of specifications for microwave ferrites*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-221 apply.

4 Saturation magnetization M_s

4.1 General

Saturation magnetization is a characteristic parameter of ferrite materials. It is widely used in theoretical calculations, for instance in computation of tensor permeability components (see IEC 60050-221). In a variety of microwave applications, saturation magnetization determines the lower frequency limit of the device, mainly due to the occurrence of so-called low-field loss when the material is unsaturated.

4.2 Object

The object is to give two similar techniques for measuring saturation magnetization. These are the vibrating coil method (VCM) and vibrating sample method (VSM).

The vibrating coil method [1][1] [2] has the advantages of easier sample mounting and simpler mechanical arrangement when measurements over a range of temperatures are required, particularly at low temperatures.

The vibrating sample method is more accurate, given a similar degree of elaboration in electronic apparatus.

The equipment needed in both cases is very similar and the calibration methods are identical. The same test samples can be used for either technique.

4.3 Theory

When a sphere of isotropic magnetic material is placed in a uniform magnetic field, the sphere becomes uniformly magnetized in the direction parallel to the applied field. The sphere now produces its own external magnetic field, equivalent to that of a magnetic dipole at the centre of the sphere and orientated parallel to the direction of magnetization.

If a small detection coil (in practice a pair wound in opposition) is now vibrated at small amplitude, close to the sample sphere and in a direction at right angles to the applied field, a voltage e_s, will be induced in the coil, proportional to the rate of change of flux φ_s due to the sample at the mean coil position x_0 whose value is given by

$$e_s = -N \cdot \left(\frac{d\varphi_s}{dx} \right)_{x_0} \cdot \frac{dx}{dt} \tag{1}$$

where N is the number of turns on the coil.

The motion of the coil, in the x-direction, is given by

$$x = x_0 + \delta \sin \omega t \tag{2}$$

where

x is displacement at time *t*;

ω is angular frequency;

δ is vibration amplitude.

If the unknown sample is now replaced by a calibrating sample of known saturation magnetization M_c and volume V_c, inducing a voltage e_c, the magnetization of the sample M_s may be found by comparison:

$$\frac{M_s}{M_c} = \frac{e_s}{e_c} \cdot \frac{V_c}{V_s} \tag{3}$$

If the induced voltages e_s and e_c give rise to readings E_s and E_c from the apparatus, then

$$M_s = M_c \cdot \frac{E_s}{E_c} \cdot \frac{d_c^3}{d_s^3} \tag{4}$$

where d_s and d_c are diameters of the sample and calibrating spheres, respectively.

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[1] Figures in square brackets refer to the bibliography.

Identical equations apply in the VSM case, when the sample is vibrated while the coil remains stationary.

4.4 Test sample

For the dipole assumption to be valid, the test sample shall be a sphere, whose deviation from roundness is not more than 0,5 %. The percentage deviation from roundness is defined as

$$\left(\frac{\text{max. diameter} - \text{min. diameter}}{\text{min. diameter}}\right) \times 100 \qquad (5)$$

For most ferrite materials, a diameter of about 2,5 mm is suitable. If it is less than 1 mm, a reasonable signal-to-noise ratio will be difficult to achieve, particularly when M_s is low. Spheres larger than about 4 mm are less convenient to make and it is not so easy to maintain a uniform applied field over the volume of the sphere.

It may be permissible to use other than spherical samples, provided that the induced voltage can be shown to be a linear function of the magnetization to within the accuracy required, and that the calibration sample has identical dimensions to the samples to be measured.

4.5 Measuring apparatus for the vibrating coil method (VCM)

4.5.1 Arrangement of detection coils and sample

A schematic diagram of the arrangement of the detection coils and the sample is shown in Figure 1. Figure 2 indicates the directions of the applied and sample fields.

The sample is rigidly mounted between the pole-pieces of an electromagnet, in such a way that its position relative to the detection coils is reproducible to ±0,1 mm in any direction. All parts of the sample holder shall be made of non-magnetic material.

The detection coils are an identical pair wound in series opposition. They are attached to the vibrator by a rigid, non-magnetic arm and are located as close to the sample as practicable. Their axes are normally parallel to the direction of vibration, but other configurations are acceptable.

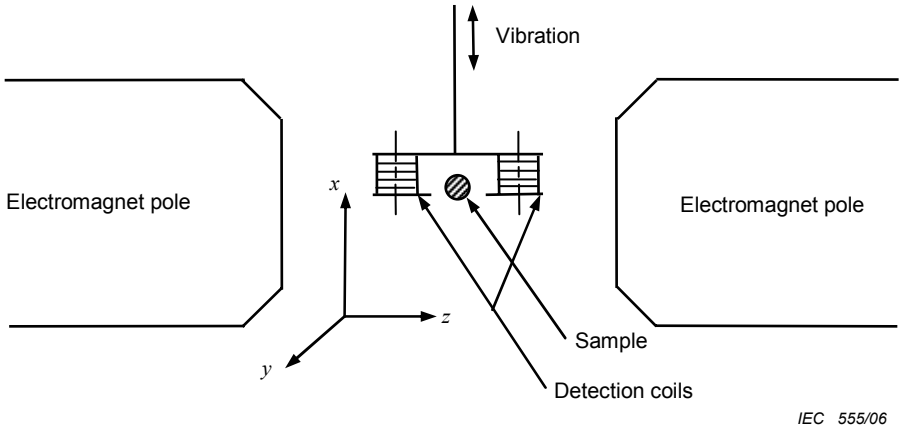


Figure 1 – Vibrating coil method – Sample and coils arrangement

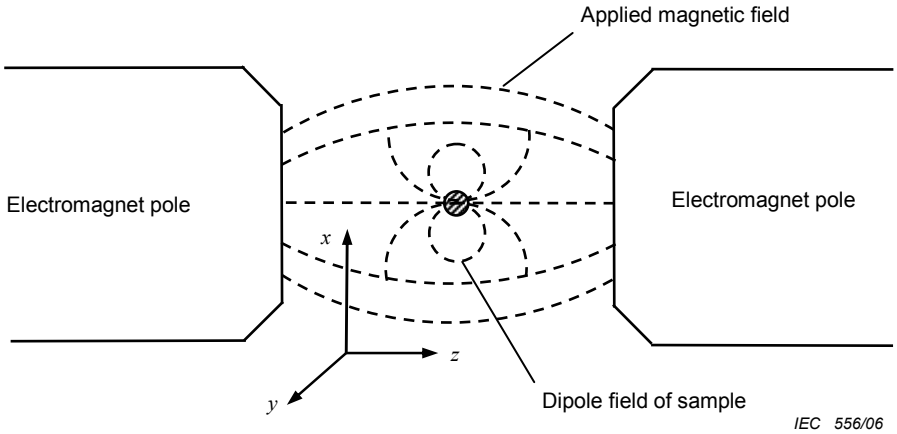


Figure 2 – Magnetic field configuration

The direction of vibration (the x-direction) is at 90° to the z-axis of the electromagnet (Figure 1), i.e. perpendicular to the magnetostatic field direction, and the amplitude shall be of the order of 0,05 mm to 0,5 mm. The frequency is not critical, but would normally be between 20 Hz and 200 Hz, although frequencies outside that range are acceptable. Motion of the coils in the z- and y-directions shall be limited by means of suitable mounting to not more than 1 % of that in the x-direction. Some means of stabilizing the vibration amplitude by use of a feedback loop may be incorporated if required.

4.5.2 The electromagnet

The magnetostatic field shall be capable of fully saturating a spherical specimen of the material to be measured. For most microwave ferrites, a field of 300 kAm^{-1} will be adequate, but for the hexagonal, barium-based ferrites, a field up to 500 kAm^{-1} may be needed. The current supply to the electromagnet shall be such as to maintain the field stable to 0,5 %.

At the mean position of the detection coils, the transverse field shall be not more than 1 % of the longitudinal field (H_z).

Since the uniformity of the field is dependent on the field-strength, measurements shall always be made at the applied field at which calibration and zero-setting (see 4.8) have been carried out.

4.5.3 Elimination of applied field effects

If the applied field were wholly uniform and had no radial components, while the direction of vibration was exactly at right angles to the applied field, the theory of 4.3 could be applied directly to the experimental arrangement of Figure 1.

However, as indicated in Figure 2, the applied field is not uniform, and its direction and magnitude vary from point to point. Moreover, it is impracticable to make an identical pair of detection coils. The angle of vibration will deviate from 90° and some residual motion in the y- and z-directions will always be present.

Voltages will therefore be induced in the coils by the inhomogeneity of the applied field. The effect of H_z is considerably lessened by winding the coils in opposition, so that voltages due to H_z tend to cancel out whereas those due to the sample dipole field will add up.

However, complete cancellation cannot in general be achieved with one pair of coils alone. Therefore, a second pair of coils, the compensating coils, is used. These are mounted on the same formers as the sample coils, but are wound in series, so that the voltages induced by H_z are additive. A compensating voltage can then be obtained, which may be adjusted in amplitude and phase to balance out the voltage induced in the sample coils by H_z.

The effect of H_x is more difficult to eliminate because the voltages induced in the sample coils will be added in the same way as those due to the dipole field. However, in general, the variation of H_x with x will be different from that of the sample dipole field. The two signals will therefore differ in phase and may be distinguished by means of a phase sensitive detector.

4.5.4 Electronic instrumentation

A schematic diagram of the measuring apparatus is shown in Figure 3. The vibrator is driven by a low-frequency oscillator (9), which may be tunable, and a power amplifier. The amplitude of the oscillator output and the gain of the power amplifier shall be sufficiently stable to provide a constant drive to the vibrator to within ±0,3 %, after warm-up. If this is not possible, some means of stabilizing the vibration amplitude shall be provided. The oscillator frequency shall be stable to 0,05 % after warm-up.

The output from the compensating coils (1(c)) is balanced against that of the sample coils (1(s)) by means of the difference amplifier (4), using the variable attenuator (2) and phase shifter (3). The phase shifter shall be fully variable over 360° and its resolution shall be at least ±0,1°. Neither the phase shifter nor the attenuator needs to be calibrated.

The difference amplifier shall have a low enough noise level at low frequencies to allow precise zero setting. The exact requirements will depend on the design of the coils and other equipment. A variable gain control may be incorporated.

The low-pass filter (5) shall reduce all harmonics by at least 20 dB with respect to the fundamental frequency.

The selective amplifier, which is tuned to the oscillator frequency, shall have a bandwidth of the order of 1 % and shall be tunable if the oscillator is not tunable.

The phase-sensitive detector (7) shall have a resolution better than 3° and either the reference or signal channel shall be variable over 360° in phase. The phase setting shall be independent of the amplitude of the input to either channel.

The meter (8) may be an analogue or digital type. When measurements are to be made over a range of temperatures, an X–Y-recorder may be substituted for the meter, one axis to record a linear function of magnetization, the other a linear function of temperature. Both axes shall be calibrated to the accuracy required. The temperature measuring device, normally a thermocouple, shall be in close thermal contact with the sample itself.

All the electronic instruments shall have adequate temperature stability to ensure the required accuracy over the range of ambient temperatures to be met in use.

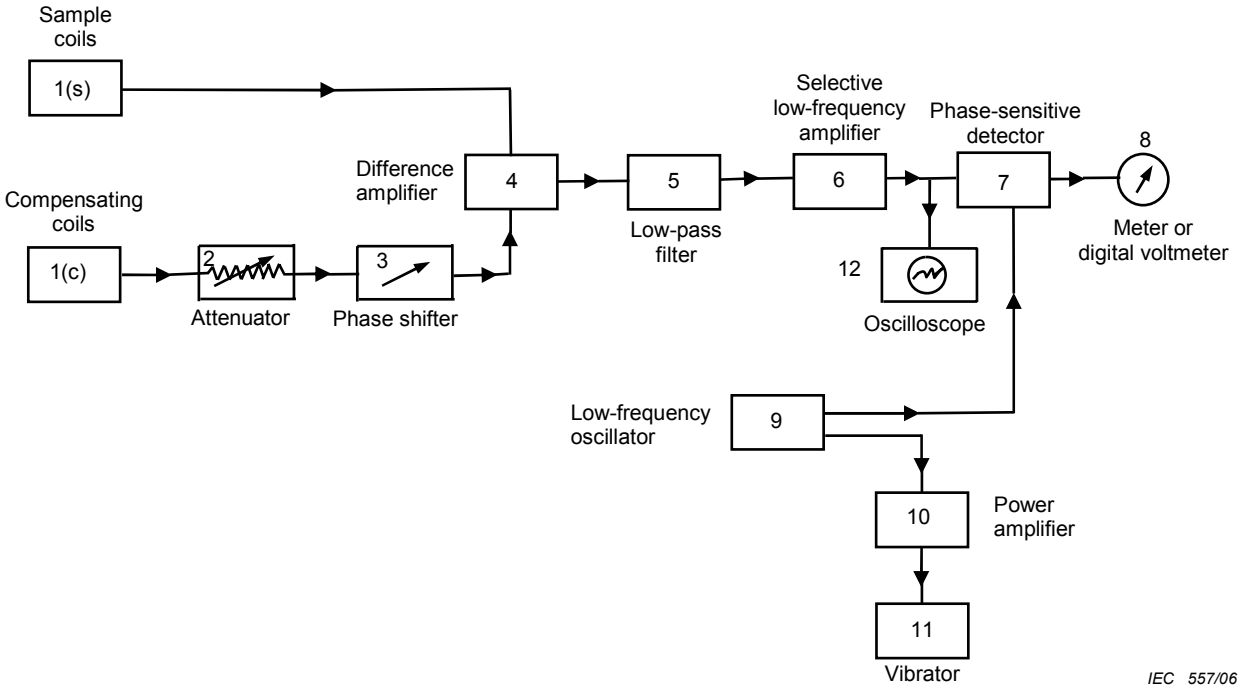


Figure 3 – Measuring apparatus (VCM)

4.6 Measuring apparatus for the vibrating sample method (VSM)

4.6.1 Arrangement of detection coils and sample

In the vibrating sample case, the detection coils (Figure 4) are rigidly mounted between the pole-pieces of the electromagnet, but in such a way that frequent small adjustments are possible. Normally, their axes are at right angles to the applied field and parallel to the direction of vibration, but other configurations [5] are acceptable. The mean sample position is on the axis of the electromagnet, normally located symmetrically with respect to the detection coils. Its position shall be reproducible to ±0,1 mm. It is rigidly mounted on a non-magnetic vibrating arm, attached to a vibrator, and is as close to the detection coils as practicable.

The direction of vibration (the x-direction) is at 90° to the z-axis of the electromagnet (Figure 4), i.e. perpendicular to the magnetostatic field direction, and the amplitude shall be of the order of 0,05 mm to 0,5 mm. The frequency is not critical, but would normally be between 20 Hz and 200 Hz, although frequencies outside that range are acceptable. Motion of the sample in the z- and y-directions shall be limited by means of a suitable mounting to not more than 1 % of that in the x-direction. Some means of stabilizing the vibration amplitude by use of a feedback loop may be incorporated if necessary.

A small permanent magnet is attached to the vibrating arm, far enough away from the electromagnet to be unaffected by it. Two small coils are mounted rigidly on either side of this magnet to detect its field. A small coil carrying a precisely controlled direct current may be used instead of the magnet.

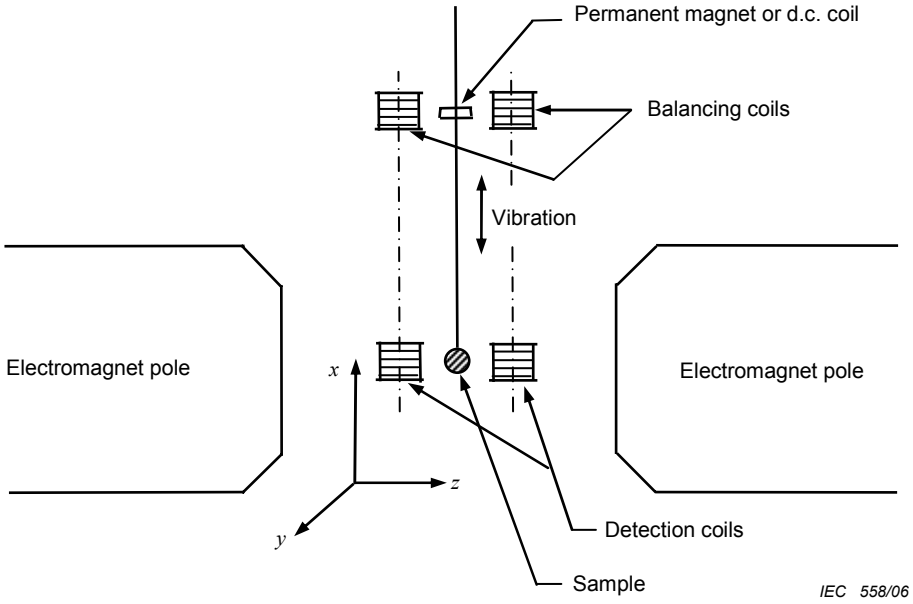


Figure 4 – Vibrating sample method – Sample and coil arrangement

4.6.2 The electromagnet

No precautions need be taken to counteract curvature and non-uniformity of applied field, provided that a uniformity of about 3 % over the volume of the sample is maintained. A radial field of up to 1 % of the longitudinal field is permissible.

The magnetostatic field shall be capable of fully saturating a spherical specimen of the material to be measured. For most microwave ferrites, a field of 300 kAm^{-1} will be adequate, but for the hexagonal, barium-based ferrites a field up to 500 kAm^{-1} may be needed. The current supply shall maintain the field stable to about 0,5 %.

4.6.3 Electronic instrumentation

A schematic diagram of the electronic instrumentation is shown in Figure 5. The simplest arrangement uses only items 1 to 8, and allows point-by-point measurements to be made at fixed temperatures. The calibrated potential divider (3) is used to balance the voltage induced in the balancing coils against that in the sample coils. The null point is observed by means of the oscilloscope (5). Magnetization is calculated from the potential divider setting.

Alternatively, the null balance may be made with the empty sample holder in position. The out-of-balance signal on insertion of a sample is then proportional to magnetization. This signal may be read directly from the meter (5) or oscilloscope. For continuous plotting of M_s as a function of temperature, an X–Y-recorder may be substituted for the oscilloscope. Greater sensitivity and better stability may be obtained by use of a phase sensitive detector (9) to detect the signal, which may then be observed by means of a meter or recorder.

If a d.c. coil (12) is used instead of a permanent magnet to obtain the balancing voltage, automatic null balancing may be achieved by feeding the output of this phase sensitive detector to the d.c. coil. The current in the coil is then directly proportional to magnetization.

The coil current may be measured by means of a d.c. ammeter in series with it, or by a high-resistance voltmeter in parallel with the coil. In the second case, variations in coil resistance due to temperature changes shall be compatible with the degree of accuracy required in M_s.

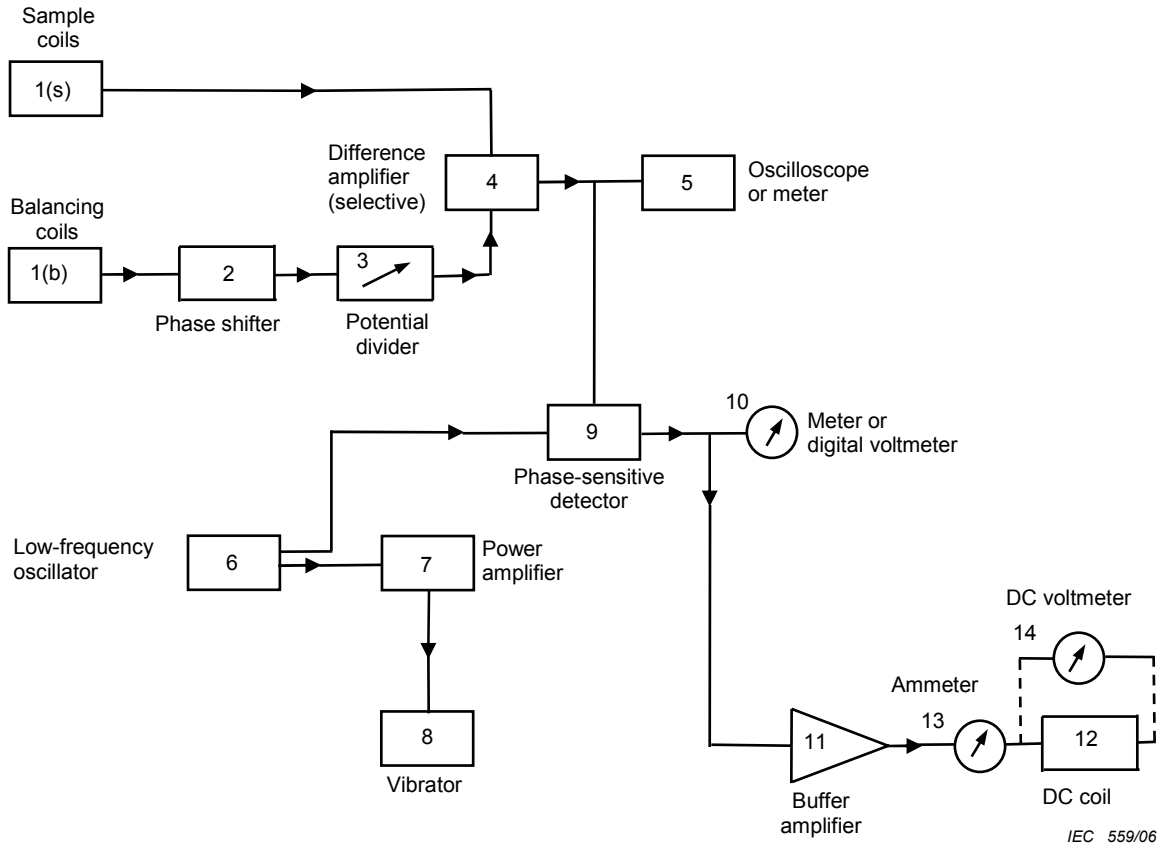


Figure 5 – Measuring apparatus (VSM)

The vibrator is driven by a low-frequency oscillator, which may be tunable, and a power amplifier. The amplitude of the oscillator output and the gain of the power amplifier shall be sufficiently stable to maintain the drive to the vibrator at a constant level, to within 0,3 % after warm-up. If this is not possible, some means of stabilizing the vibration amplitude shall be provided. The oscillator frequency shall be stable to within 0,05 % after warm-up.

The potential divider shall be continuously variable with a resolution of 0,01 % or better and shall be calibrated to the accuracy required.

The difference amplifier shall have a sufficiently low noise level and shall incorporate, or be followed by, a selective amplifier with a bandwidth of the order of 3 %, tuned to the oscillator frequency. The selective stage shall be tunable if the oscillator is not tunable.

The requirements for the phase-sensitive detector are not stringent. A resolution of 10° is adequate. The phase setting shall be independent of the amplitude of the input to either channel.

The meters may be analogue or digital types. When measurements are to be made over a range of temperatures, an X–Y-recorder may be substituted for the meter, one axis to be a linear function of magnetization, the other a linear function of temperature. Both shall be calibrated to the accuracy required. The temperature measuring device, normally a thermocouple, shall be in close thermal contact with the sample itself.

All the electronic equipment shall have adequate temperature stability to maintain the required accuracy over the range of ambient temperatures generally encountered in use.

4.7 Calibration

4.7.1 Comparison method

This method, which is equally applicable to either the vibrating coil or the vibrating sample methods, calls for a standard sample whose saturation magnetization is accurately known. The most usual material for the standard is pure nickel, but other materials may be used if their saturation magnetization is known accurately enough.

The calibration sample shall be a sphere (if the samples to be measured are spheres) and be of a similar order of size. (If samples other than spheres have to be measured, calibration samples with identical dimensions shall be used.) The calibration sphere shall show a deviation from roundness of not more than 0,5 % and its mean diameter shall be known to within 0,1 %. Standard metallic spheres shall be fully annealed before use.

The density of the material to be used as a standard shall first be determined. The generally accepted value for the saturation magnetization of 99,995 % pure nickel with a density of 8,90 g·cm^{-3}, is 485,6 kAm^{-1} at 23 °C. For less dense material:

$$M_{\mathrm{s}} = \frac{485{,}6 \times \text{density}}{8{,}90} \quad (\mathrm{kAm^{-1}}) \tag{6}$$

However, the actual value for a specific sample may differ from this by as much as 1 % [3], depending on purity, state of strain, applied field, or ambient temperature. The accuracy of the comparison method is therefore limited.

4.7.2 "Slope" method

This method, which is equally applicable to either the vibrating coil or the vibrating sample methods, is based on the observation that the voltage induced in the detection coils by a spherical specimen is directly proportional to the applied field over the lower region of the magnetization curve [4]. Furthermore, the constant of proportionality is independent of the permeability, provided that the latter is sufficiently high.

According to 4.3, the voltmeter reading E_{x}, for any sample x, can be written:

$$E_{\mathrm{X}} = kM_{\mathrm{X}}d_{\mathrm{X}}^{3} \tag{7}$$

where

M_{x} is the magnetization of the sample at a (low) value of applied magnetostatic field strength H_0;

d_{x} is the sample diameter;

k is the constant.

In the region below saturation, the (linear) relationship between M_{x} and H_0 is given by the following equations:

$$M_{\mathrm{x}} = (\mu_{\mathrm{x}} - 1)H_{\mathrm{i}} \tag{8}$$

$$H_{\mathrm{i}} = H_0 - NM_{\mathrm{x}} \tag{9}$$

where

H_{i} is the magnetostatic field strength inside the sample;

μ_{x} is the relative permeability of the sample;

N is the demagnetization factor which is equal to one-third for a perfect sphere.

Elimination of H_i between equations (8) and (9) yields:

$$H_0 = \left(\frac{1}{\mu_x - 1} + N \right) M_x \tag{10}$$

Elimination of M_x between equations (7) and (10) yields:

$$E_X = k \frac{H_0}{1/(\mu_x - 1) + N} d_X^3 \tag{11}$$

The linear part of the graph of E_x as a function of H_0 has a slope which, according to equation (11), is equal to

$$\frac{\Delta E_X}{\Delta H_0} = \frac{k d_X^3}{1/(\mu_x - 1) + N} \tag{12}$$

If μ_x is sufficiently high, for example 2 000, the first term in the denominator can be neglected in comparison with N, and the parameter k can be expressed as

$$k = \frac{\Delta E_x / \Delta H_0}{3 d_X^3} \tag{13}$$

to within an error of 0,15 %.

A deviation from roundness of 0,25 % leads to a maximum error in N of 0,25 % [3].

The value of k thus obtained, using a high-permeability calibration sample, can be inserted into equation (7) which is subsequently applied to the unknown sample, at saturation. The saturation magnetization of the unknown sample M_{su} is, to within 0,4 %, given by

$$M_{su} = \frac{E_{su}}{k d_u^3} = E_{su} \frac{3 d_c^3}{(\Delta E_c / \Delta E_0) d_u^3} \tag{14}$$

where

E_{su} is the voltmeter reading for the saturated unknown sample, and

subscripts c and u refer to the calibration sample and unknown sample, respectively.

This method does not require an absolute calibration standard.

4.8 Measuring procedure

4.8.1 Zero setting – Vibrating coil method

The electromagnet current is switched on, with the empty sample holder between the poles. The detection coils are allowed to vibrate. The attenuator and phase shifter are adjusted to obtain a minimum output from the selective amplifier, as observed on the oscilloscope.

The applied field is then altered and the attenuator and phase shifter settings checked. If these have changed significantly, the location of the coils is adjusted and the zero re-set, until a position is found at which the zero setting is sufficiently independent of applied field over the range of interest.

A calibration sample is placed in the holder and the phase sensitive detector adjusted until a maximum reading is obtained on the voltmeter.

4.8.2 Zero setting – Vibrating sample method

The balancing coils are first made as insensitive as possible to the exact position of the reference magnet (or d.c. coil). In the absence of any signal from the detection coils, the balancing coils are rotated about the x-axis for maximum output. They are then adjusted in the z-direction for minimum output, in the y-direction for maximum output and the x-direction for a maximum (if the coils are short) or minimum (if they are long). The output is now independent of small changes in the position of the magnet.

The balancing coils are then firmly fixed in position and the above adjustments are not normally repeated.

A sample is placed in the holder and similar adjustments carried out for the sample coil in the absence of a signal from the balancing coils.

4.8.3 Measurement

All the electronic equipment shall be switched on at least 30 min before starting measurements, to allow it to stabilize at the ambient temperature. The zero reading is checked with the sample holder empty and the apparatus adjusted if necessary.

A calibration sample is placed in the holder and the reading checked to ensure that it is correct for that particular specimen at the ambient temperature.

The diameter of the spherical sample is measured making at least five separate micrometer or microscope measurements. The deviation from roundness is calculated according to equation (5).

The sample is fixed in the holder and the applied field set to the required value.

In the VSM case, the potential divider setting is adjusted to obtain a null reading on the oscilloscope or, alternatively, if the null has been obtained for the empty sample holder, the meter reading is noted. If automatic null balancing with a d.c. coil is being used, the coil current is observed.

In the VCM case, the meter reading is noted.

The temperature of the sample is also observed. If measurements are to be made over a range of temperatures, the temperature is set to the lowest value to be used, allowing enough time for the environmental chamber to stabilize, and then increased at not more than 3 °C/min until the whole temperature range of interest has been covered.

4.9 Calculation

The readings are converted into values of magnetization, using either equation (4) or (14) according to whether the calibration method was as described in 4.7.1 or 4.7.2.

4.10 Accuracy

The accuracy of either VCM or VSM depends on the method of calibration. If the comparison method is used, a systematic error of up to 1 % may be introduced because of uncertainty in the magnetization of the calibration sample. The slope method is somewhat better because the absolute value of M_C is not needed. In that case, the error due to uncertainty in the calibration may be kept to less than 0,5 %.

The relative error for the VCM is typically ±3 %.

The relative error for the VSM is typically ±1,5 %.

The relative errors depend on the value of M_s, being greater for low values of saturation magnetization.

4.11 Data presentation

Values of M_s obtained by either method shall be quoted as follows:

saturation magnetization at a temperature of θ °C: M kAm^{-1} ± estimated error, where the number M is given to three significant figures.

If M_s has been plotted as a function of temperature, the actual curve shall be given together with an estimate of the accuracy of both M_s and temperature measurements.

The report shall also include the unique identity of the sample.

5 Magnetization (at specified field strength) M_H

5.1 General

For theoretical computations of tensor permeability components, knowledge of the saturation magnetization of the material is necessary (see IEC 60050-221). However, in general, the ferrite material in a microwave component is not completely saturated.

For example, in the recently developed so-called latching devices, the ferrite is in a state of remanence. Therefore, a method has been sought whereby more general information on the hysteresis loop properties of a material can be obtained. The applicability of this method is somewhat limited by the fact that the test specimen has to be a toroid, or at least a closed magnetic circuit that can, with sufficient accuracy, be expressed in terms of an equivalent toroid.

5.2 Object

The measuring method to be described has been developed primarily in order to measure magnetization. However, it also permits simultaneous measurement of a number of other magnetic properties, for instance remanent magnetization and coercivity when the material is in a cyclic magnetic condition. The “squareness ratio”, M_r/M_H, of the material may be calculated, and the hysteresis loop can be continuously displayed on an oscilloscope during measurements. The latter fact enables the sensitivity of the material to mechanical stress to be checked qualitatively.

By placing the test specimen in a programmed temperature test chamber all quantities can be obtained as functions of temperature. By allowing for a sufficient temperature sweep range, the Curie temperature and, for certain materials, the compensation temperature may be determined.

5.3 Theory

In a ferrite toroid, the following relation between flux density B, magnetization M and field strength H is valid:

$$B = \mu_0 (H + M) \tag{15}$$

where μ_0 is the magnetic constant.

If the ratio of outer to inner diameter of the toroid is close to unity, all the field quantities can be assumed to be reasonably constant over the toroid cross-section.

If H is varied periodically and symmetrically and B is measured simultaneously and plotted as a function of H in a Cartesian co-ordinate system, a dynamic $B(H)$ loop is obtained (Figure 6a). This curve can be changed into an $M(H)$ loop by subtracting from B a quantity equal to $\mu_0 H$ and dividing by μ_0 (Figure 6b). If the variation in H is sufficiently large, the height of the curve becomes independent of any further increase in H and equal to M_s. In this case, the intercepts of the loop with the H-axis correspond to the cyclic coercivity H'_{cJ}.

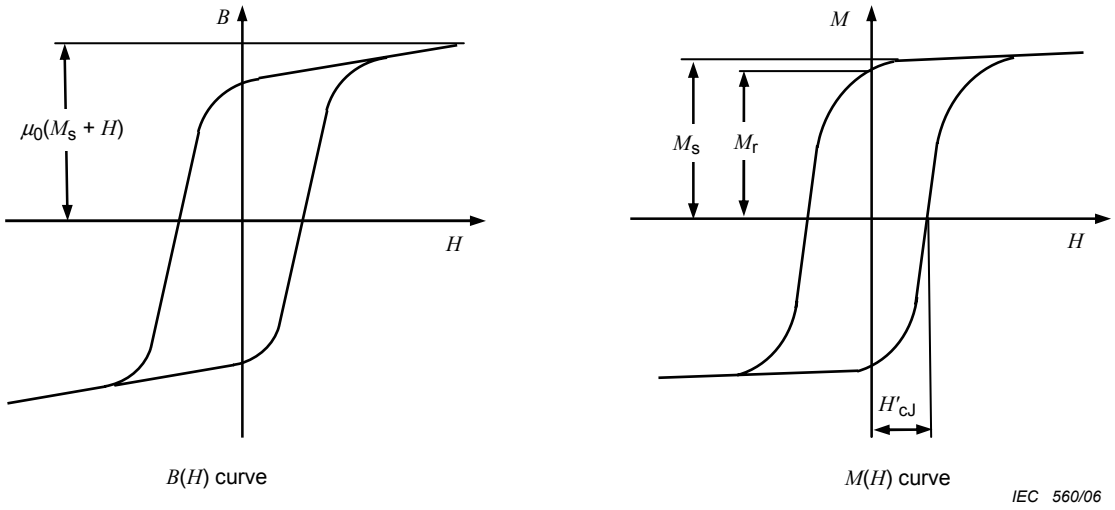


Figure 6 – Hysteresis curves for a magnetic material: *B*(*H*) curve, *M*(*H*) curve

If a winding consisting of N_1 turns is uniformly distributed over a toroidal core having rectangular cross-section, a current I through that winding gives rise to a magnetic field inside the core with a mean value equal to

$$H = \frac{N_1 I}{2\pi r_m} \tag{16}$$

where r_m is the mean radius of the core calculated as

$$r_m = \frac{\ln(r_2 / r_1)}{(1/r_1) - (1/r_2)} \tag{17}$$

where r_1 and r_2 are the inner and outer radii of the toroid, respectively (see IEC 60205) .

If a secondary winding of N_2 turns is uniformly distributed over the same core, an electromotive force E, proportional to the time derivative of the flux density in the core is induced in that winding:

$$E = -k \frac{dB}{dt} \tag{18}$$

where

k is $N_2 A_e$;

A_e is the effective cross-section of the specimen, as defined in 5.5.

Had the same two windings been placed on a non-magnetic core, the induced voltage would have been proportional to the time derivative of the field strength:

$$E' = -k\mu_0 \frac{\mathrm{d}H}{\mathrm{d}t} \tag{19}$$

The arrangements described above correspond to a ferrite-core and an air-core transformer, respectively. If two such transformers, one of either kind, are connected in series opposition, as shown in Figure 7, the total output voltage U is equal to

$$U = E - E' = -k\left(\frac{\mathrm{d}B}{\mathrm{d}t} - \mu_0 \frac{\mathrm{d}H}{\mathrm{d}t}\right) \tag{20}$$

whence

$$U = -k\mu_0 \frac{\mathrm{d}M}{\mathrm{d}t} \tag{21}$$

By integrating the voltage U, a voltage-time integral proportional to M can be obtained. Thus, since H is proportional to I, there are two electrical quantities that may be used to give an analogue representation of the $M(H)$ loop.

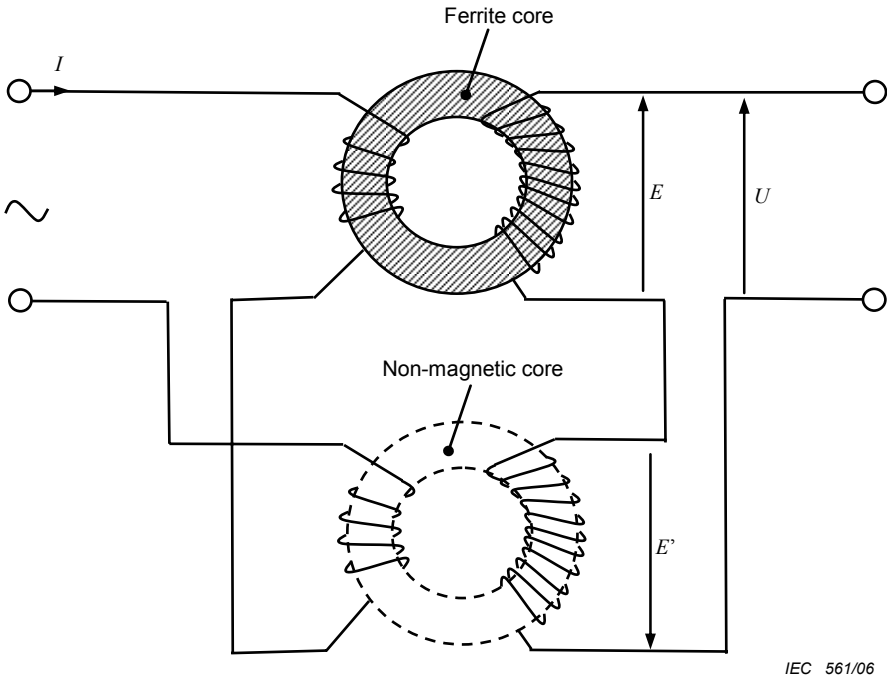


Figure 7 – Test sample with compensation unit

5.4 Test specimen

A toroid is made from the material to be investigated. An example of suitable dimensions for the toroid is given in Figure 8. The dimensions may be slightly changed, but the ratio of inner to outer diameter shall always exceed 0,7.

A minor portion of one of the flat sides of the specimen is silver-coated. A suitable silver preparation should show good adhesion and solderability after curing.

Dimensions in millimetres

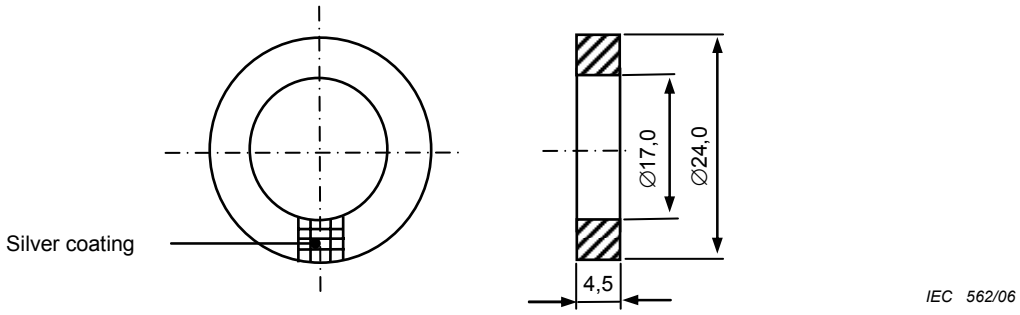


Figure 8 – Test specimen

A high melting-point solder (melting-point approximately 310 °C) is prepared by making an alloy of about 90 % by weight of lead and the remainder tin. This alloy, which can be used in the same way as ordinary solder, is used to fix a thermocouple (copper-constantan) to the silver-coated portion of the core surface. This thermocouple measures the real core temperature with sufficient accuracy. Some sort of protective coating may be applied to the thermocouple junction to minimize direct heat radiation pick-up.

Heating (such as during silver curing or soldering) may be harmful to certain ferrite materials. If this is the case, other means for assuring good thermal contact with the thermocouple should be considered.

The next step is to place two windings on the core: the first is the search coil, consisting of a single layer containing 200 turns of 0,2 mm diameter copper wire, insulated with a heat resistant lacquer such as polyamide. The winding should be spread as evenly as possible over the core excluding only the silver-coated part. Then the drive coil is wound on top of the search coil. The drive coil consists of 70 turns of 0,5 mm diameter copper wire, insulated with heat resistant lacquer. The figures given above should be taken as examples only; other numbers of turns may equally well be used provided that they are taken into account in the calculations.

5.5 Measuring apparatus

The test specimen and a similar transformer (compensation unit), wound on a non-magnetic core of the same dimensions as the ferrite toroid, are connected to a measuring circuit as shown in Figure 9. A sinusoidal power source delivering 0 V to 5 V r.m.s. with a frequency less than or equal to 60 Hz is connected to the primary windings through a resistor R_i. The resistor is made of a short length of constantan wire and has, in the example given here, a resistance of 0,0963 Ω. (If care is exercised, the resistance may be increased somewhat to allow for a lower sensitivity of the oscilloscope X input.) The voltage drop across the resistor U_x is fed to the horizontal input of an oscilloscope.

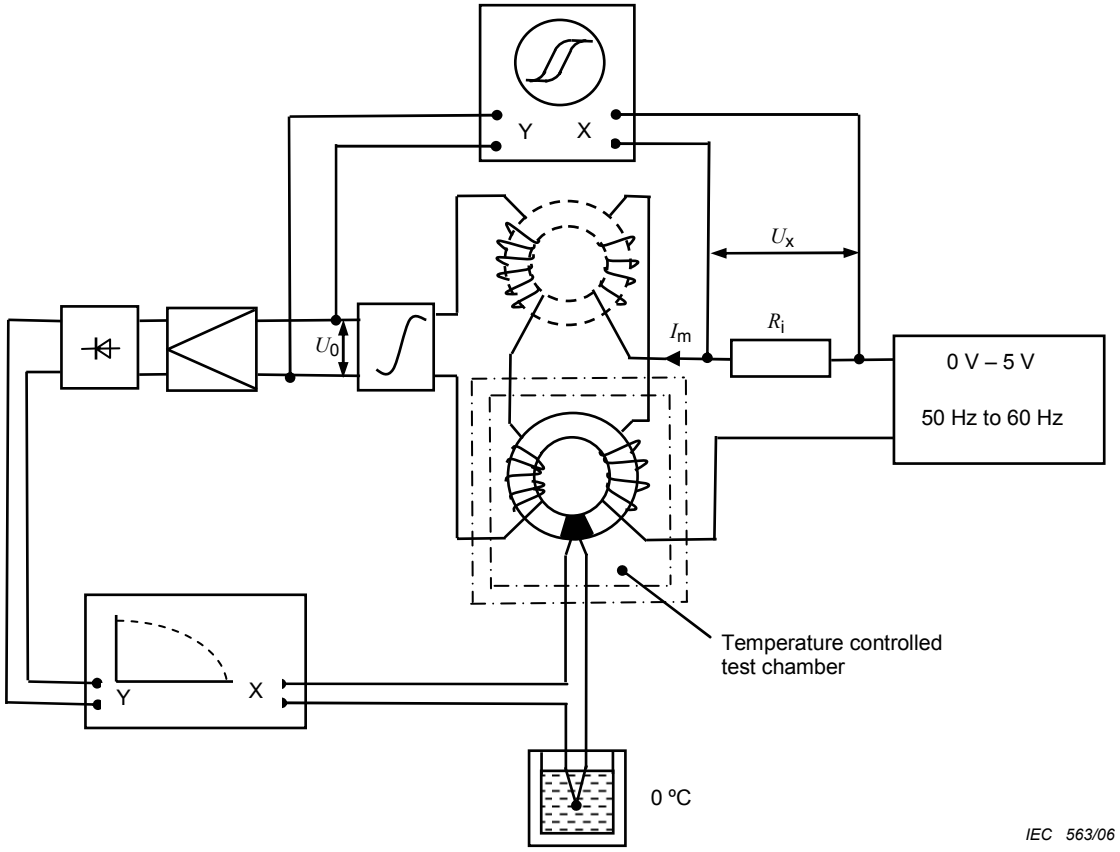


Figure 9 – Measuring circuit for determining magnetization (at specified field strength) M_H

This voltage is proportional to the drive current I_m and hence to the magnetic field strength H_m. It follows that

$$U_X = I_m R_i = \frac{H_m l_m}{N_1} R_i \tag{22}$$

where

l_m is the mean flux path length;

N_1 is the number of primary turns.

An input signal of 1 V corresponds to a field strength equal to

$$H_m = \frac{N_1}{l_m R_i} \tag{23}$$

or, with the figures used in the example quoted, $11{,}51 \times 10^3$ Am^{-1}.

Therefore, an oscilloscope input voltage of 1 mV corresponds to a field strength of 11,51 Am^{-1}.

The output voltage from the two secondary windings, connected in series, is proportional to the time derivative of M. To obtain a signal proportional to M, it has to be integrated, which is done in a Miller integrator.

A Miller integrator may be built with the aid of an operational amplifier according to Figure 10:

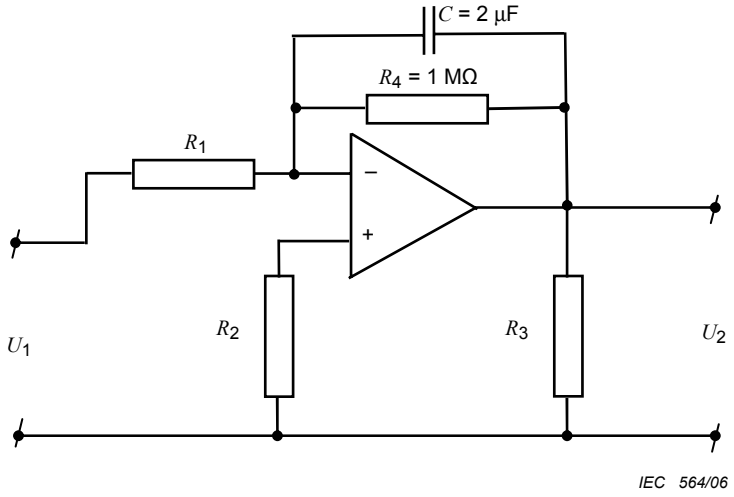


Figure 10 – Miller integrator

In order to have satisfactory performance from the integrator, its effective time constant $RC \times G$ (where G is the amplifier gain) shall exceed the reciprocal of the measuring frequency by a factor of at least 100. It should also be checked that the integrator does not introduce phase shift at low frequency.

The integrator output voltage is equal to

$$U_2 = \frac{\mu_0 M \ N_2 A_e}{R_1 C} \cdot \frac{G}{G+1} \tag{24}$$

where

$$A_e = \frac{h \cdot (\ln(r_2/r_1))^2}{(1/r_1) - (1/r_2)} \tag{25}$$

is the effective cross-sectional area of the core and N_2 is the number of secondary turns.

This signal U_2 is fed to the vertical input of the oscilloscope. Typically, an input voltage of 1 mV corresponds to an M_H value of approximately 2 kAm^{-1}.

The bandwidth and sensitivity of the oscilloscope shall be adequate. A low-frequency limit of less than 0,25 Hz (preferably d.c.) and an upper limit of more than 10 kHz will give satisfactory results. The sensitivity of the X and Y amplifiers shall exceed 2 mm per millivolt.

The oscilloscope Y input signal is also amplified to a level of 10 V to 20 V and subsequently rectified in a peak-sensing rectifier. The rectified signal is fed to the Y input of an X-Y-recorder. The X input of the recorder is fed by the thermocouples in such a way that the recorder deflection is directly proportional to the core temperature in degrees Celsius. Thus a diagram showing the temperature dependence of M_H can be obtained.

5.6 Calibration

The oscilloscope inputs are calibrated with the aid of an external, high precision voltage source. The recorder is adjusted to correct sensitivity with regard to the temperature interval and the expected maximum value of M_H in that region.

The output from the power source is adjusted (with the aid of the oscilloscope) so that the field strength amplitude is equal to $n \times H'_{cJ}$ (where n is an integer, typically 5) at room temperature. This value (that is the width of the oscilloscope display) shall be kept constant during the entire measurement.

5.7 Measuring procedure

All the electronic equipment shall be switched on approximately 30 min before measurement, to ensure adequate stability. The test specimen is mounted in the temperature controlled test chamber and its windings and thermocouple leads are connected to the measuring circuit. The X- and Y-amplifiers of the oscilloscope are calibrated.

The drive current is increased so that the maximum magnetic field strength is equal to the desired value, usually five times the coercivity. The sensitivity of the X-Y-recorder is adjusted and its Y-axis calibrated against the value of M read off the oscilloscope screen.

The temperature of the test chamber is brought down to the lowest temperature of interest. The measurement starts from this point and the core temperature is allowed to rise so slowly (typically less than 3 °C/min) that the test specimen can be considered to be in reasonable thermal equilibrium. The maximum value of M, (M_H), is automatically recorded as a function of temperature. At certain temperatures, readings of remanent magnetization and coercivity are taken. Alternatively, photographs may be taken for more detailed study of loop configuration.

The measurement is terminated when the temperature has reached an appropriate value; normally a temperature a little above the Curie point is chosen.

5.8 Calculation

The oscilloscope readings, whether obtained from direct observation or photographs, are converted into values of magnetization and field strength using the expressions given in 5.5. The "squareness ratio", M_r/M_H, is calculated using the values thus obtained. The recorder curve is self-explanatory and requires no further calculation.

5.9 Accuracy

The measuring accuracy varies with M_H, the error generally increasing when a transition temperature is approached and M_H becomes small. Sufficiently far from these points, the systematic error is, however, very small, of the order of ± 1 %, provided that the measuring circuit is correctly built. The uncertainty introduced by the readout instrumentation is additional to this. This quantity may be very difficult to establish, but the following relative errors are typical of data obtained according to this method:

$M_H \rightarrow \pm$ 3 % (max.)

$H'_{cJ} \rightarrow \pm$ 5 %

Curie point $\rightarrow \pm$ 2 °C

Squareness ratio $\rightarrow \pm$ 6 %

5.10 Data presentation

Values of M_H obtained by this method shall be quoted as follows:

– magnetization at a magnetic field strength equal to n times the coercivity and at a temperature of θ °C: M kAm^{-1} ± 3 %;

or, in the case of remanent magnetization:

– remanent magnetization when the magnetic field strength has been decreased from n times the coercivity to zero at a temperature of θ °C: M kAm^{-1} ± 3 %, where the number M is given to three significant figures.

In cases where M_H is plotted against temperature, the actual curve shall be given together with a statement concerning the estimated accuracy.

The report shall also include the unique identity of the sample.

6 Gyromagnetic resonance linewidth ΔH and effective Landé factor g_{eff} (general)

6.1 General

The gyromagnetic resonance linewidth and the effective Landé factor are properties which are of fundamental importance in determining the performance of devices operating at or near gyromagnetic resonance, and are necessary for the computation of tensor permeability components in that region. Determination of these quantities involves the measurement of a resonance phenomenon in which both frequency and applied magnetostatic field strength are critical parameters. Stability, both dimensional (of the cavity) and electrical, thus becomes of primary importance, particularly when it comes to investigating materials having very narrow resonance linewidths.

6.2 Object

To describe a method that can be used for measuring the gyromagnetic resonance linewidth and the effective g-factor of isotropic microwave ferrites over the approximate frequency range 0,3 GHz to 30 GHz. It may be used for materials having wide as well as narrow linewidths.

6.3 Theory

The method applies exclusively to the so-called Kittel's mode or uniform precession resonance; resonances in which other magnetostatic modes are involved or which suffer from ambiguity due to insufficient magnetic saturation are disregarded.

The value of the field for maximum absorption or resonance H_0 may be theoretically computed in terms of the saturation magnetization of the sample M_s, the demagnetizing factors N_x, N_y, N_z, the effective g-factor g_{eff} and the measuring frequency f_0. If the specimen has the shape of a small sphere, the relationship reduces to the simple formula:

$$f_0 = \frac{\gamma \mu_0 H_0}{2\pi} \tag{26}$$

where

γ is the gyromagnetic ratio;

μ_0 is the magnetic constant.

If, on the other hand, the specimen is shaped as a disk with a diameter sufficiently larger than its thickness, and the external field is perpendicular to the surface, the formula becomes:

$$f_0 \approx \frac{\gamma \mu_0}{2\pi} [H_0 - (1 - 3\rho) M_s] \tag{27}$$

where

ρ is the $d/D < 1/20$;

d is the thickness of the specimen;

D is the diameter of the specimen.

Recognizing that γ = 88 $g_{\text{eff}} \cdot 10^9$ $T^{-1}s^{-1}$, it is thus possible, knowing f_0, H_0 and M_s, to calculate the effective Landé factor g_{eff}.

The gyromagnetic resonance linewidth ΔH is defined as the difference between the two magnetic field strength values at which the power absorbed by the ferrite material is one-half the maximum absorption.

The method recommended for the measurement of g_{eff} and ΔH is based on the cavity perturbation concept, which requires that the specimen dimensions shall be small compared with the wavelength inside the specimen. For disk specimens to be used over the frequency range 0,3 GHz to 3,0 GHz, the quotient of diameter and thickness shall exceed 30 with the diameter meeting the requirement of 6.4.

The absorption in the specimen is measured by determining the change of power incident on the cavity required to keep the output power from the cavity at a fixed reference level.

The variation in input power may be expressed as the variation of the attenuation inserted between the monitored source and the cavity in order to maintain the reference output level. If α_0 is the attenuator reading, in decibels, with no sample present and α_r is the reading for maximum specimen absorption, then the reading $\alpha_{½}$ corresponding to a specimen absorption of half the resonance value, is given by one of the following equations:

$$\alpha_{1/2} = \alpha_0 + 10\lg 2 - 10\lg\left(10^{(\alpha_0 - \alpha_r)/10} + 1\right) \tag{28}$$

6.4 Test specimens and cavities

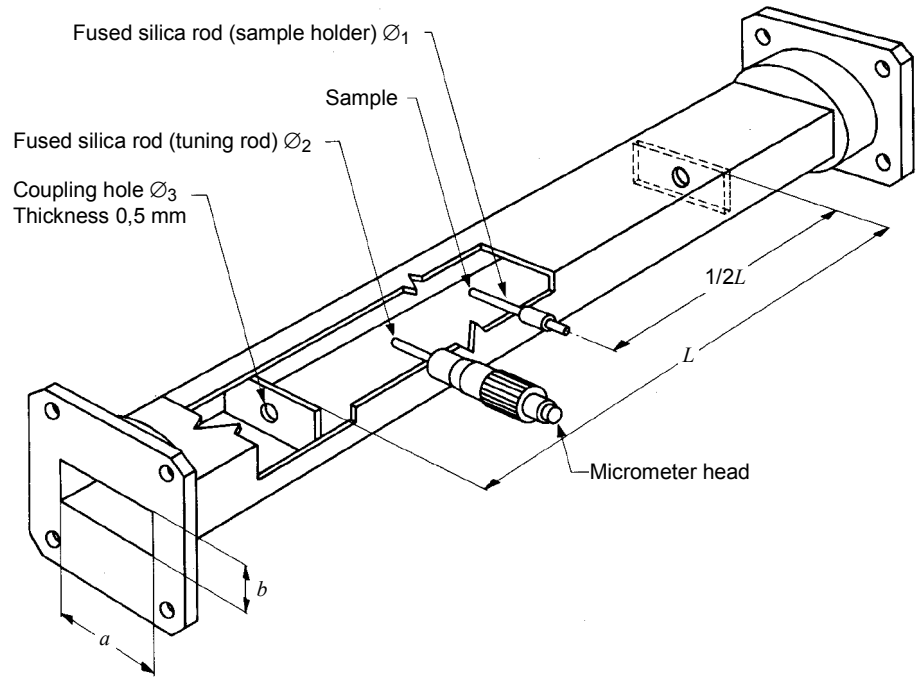
The test specimens for this method may be either spherical (for materials having linewidths greater than about 400 Am^{-1}) or disk-shaped. Dimensional restrictions appear both in the preceding and the following text.

In particular, to ensure a sufficiently small cavity perturbation, the measured values of ΔH and H_0 shall satisfy the following condition:

$$\alpha_0 - \alpha_r < 20\lg\left(1 + 0{,}06\,Q_0\,\frac{\Delta H}{H_0}\right) \tag{29}$$

where Q_0 is the Q value of the cavity without specimen.

The sample dimensions, for example the sphere diameter, shall be reduced until the loss difference meets this requirement.

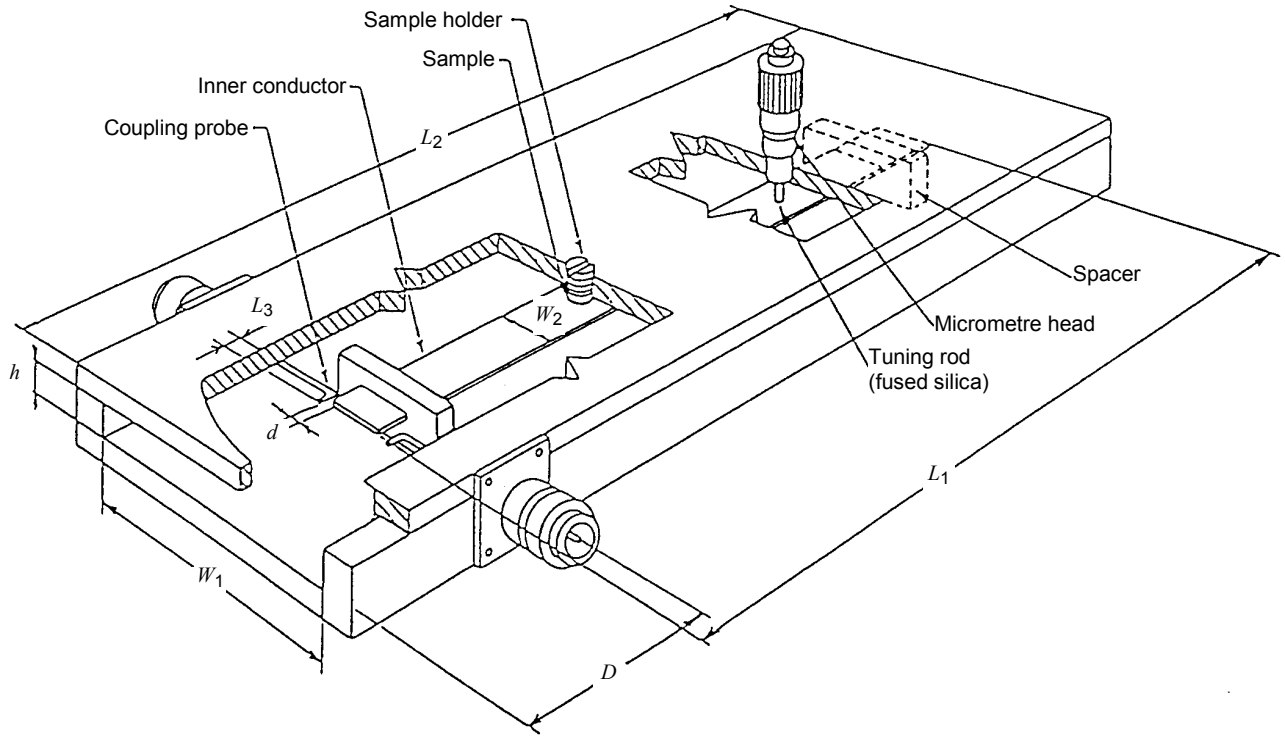


Frequency GHz	Dimension mm					
	L	***a***	***b***	**∅1**	**∅2**	**∅3**
3	278	72,14	32,04	2	6	15
10	118,4	22,86	10,16	1	3	5
30	36,9	8,636	4,318	0,5	1,5	2,5

Figure 11 – Cavity for measurement of gyromagnetic resonance linewidth and effective Landé factor

For spheres with a relatively low linewidth (less than 3 kAm^{-1}), the measurement results depend strongly on the state of surface of the samples. Ideally, they would be optically polished. In practice, a ΔH-curve may be plotted from three ΔH measurements corresponding to three progressive stages of grinding, the asymptotic ΔH value being quoted in 6.9. The state of surface of the sphere to be measured may also be indirectly defined through the grain size of the grinding abrasive.

The polishing process may introduce stress in the sample, affecting the measured value of ΔH. This effect may be minimized by annealing for a short period of time.



IEC 566/06

NOTE The spacer may be a PTFE slab typically measuring 7 mm by 2 mm by 25 mm, slightly adjustable in position.

Frequency MHz	**Dimension** mm							
	d	***D***	***h***	L_1	L_2	L_3	W_1	W_2
300	2,0	39	7	470	510	21	60	20
1 000	2,0	28	7	140	180	10	60	20

Figure 12 – Stripline resonator for measurement of gyromagnetic resonance linewidth and effective Landé factor at low frequency

By way of an example, Figure 11, illustrates a cavity of the transmission type. Dimensions yielding a loaded quality factor (Q_0) greater than 2 000 are given for three frequencies. The spherical specimen is positioned at a point of minimum electric and maximum magnetic microwave field. In Figure 11, the proper specimen position is also indicated. The specimen is mounted on a sample holder (fused silica rod). The hole for inserting the specimen into the cavity is located in the narrow cavity wall and shall not exceed 2 mm in diameter (for an X-band cavity). An additional perturbing rod is mounted in a suitable position to allow tuning by interaction with the electric field in the cavity. The input and output lines to the cavity are made to appear as matched loads by means of pads or isolators. This type of cavity design applies for spherical samples over the frequency range of 3 GHz to 30 GHz. If the measuring frequency exceeds the value given by

$$f = \frac{\gamma\mu_0}{2\pi} \cdot \frac{2}{3} M_s \tag{30}$$

the observed value of ΔH will contain contributions from the spin-wave modes excited by defects of polycrystalline ferrites [6].

For measurements between 0,3 GHz and 3 GHz, however, a disk-shaped specimen is preferable. The type of cavity recommended, in this case, is a tunable stripline resonator with both ends open-circuited as illustrated in Figure 12. As is evident from the figure, the cavity has odd-order resonances at wavelengths of about $2L$, $2/3L$..., where L is the length of the stripline inner conductor[2]. Dimensions yielding a loaded quality factor (Q_0) greater than 400 are given for two frequencies. The specimen is glued to a sample holder which is in the form of a metal plug screwed through the outer conductor so that the specimen is located in the vicinity of the centre of the inner conductor. To keep the microwave field as uniform as possible over the specimen, the sample diameter shall be less than one-third of the width of the inner conductor. The tuning rod serves to tune the cavity by additional perturbation so that measurement can be made at a predetermined frequency. Linewidths measured on disk-shaped specimens are not broadened by spin-wave loss.

The preparative process may introduce stress in the specimen affecting the measured value of ΔH. This effect may be minimized by a process of annealing for a short period of time.

6.5 Measuring apparatus

Figure 13 is a schematic diagram of the equipment required to make the measurements. Power from a suitable microwave source A operated either unmodulated or with amplitude modulation, but free from frequency modulation, is fed through a precision variable attenuator F to the cavity G, and the output power is detected and indicated on a suitable meter H. The power incident on the precision attenuator is monitored at E by means of a directional coupler and crystal detector, and this incident power is kept constant throughout the measurement by means of a variable attenuator C. The microwave frequency, which is monitored at B, can be kept unchanged because the tuning rod may be used to tune the cavity to the generator frequency. An adjustable magnetic field of sufficient stability perpendicular to the microwave magnetic field is applied to the specimen. The non-homogeneity of the applied field over the specimen shall be negligible compared to the linewidth being measured.

6.6 Measuring procedure

Set the generator frequency as closely as possible to the measuring frequency. Tune the cavity for maximum transmission with the aid of the tuning rod. Establish an input level measured at E, a setting α_0 on the precision attenuator, and an output level measured at H. Take this output level as a reference value.

Insert the specimen into the cavity. This operation should have a negligible effect on the output level. Apply the magnetic field and adjust it for maximum absorption (minimum transmission). Determine the new setting α_r on the precision attenuator which restores the output level to the reference value. Determine the microwave frequency f_0 and the applied magnetostatic field strength H_0.

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[2] The use of a dielectric sample holder may be preferred; this will necessitate the use of a larger specimen for a given sensitivity but the location of the specimen within the outer conductor is then not so critical.

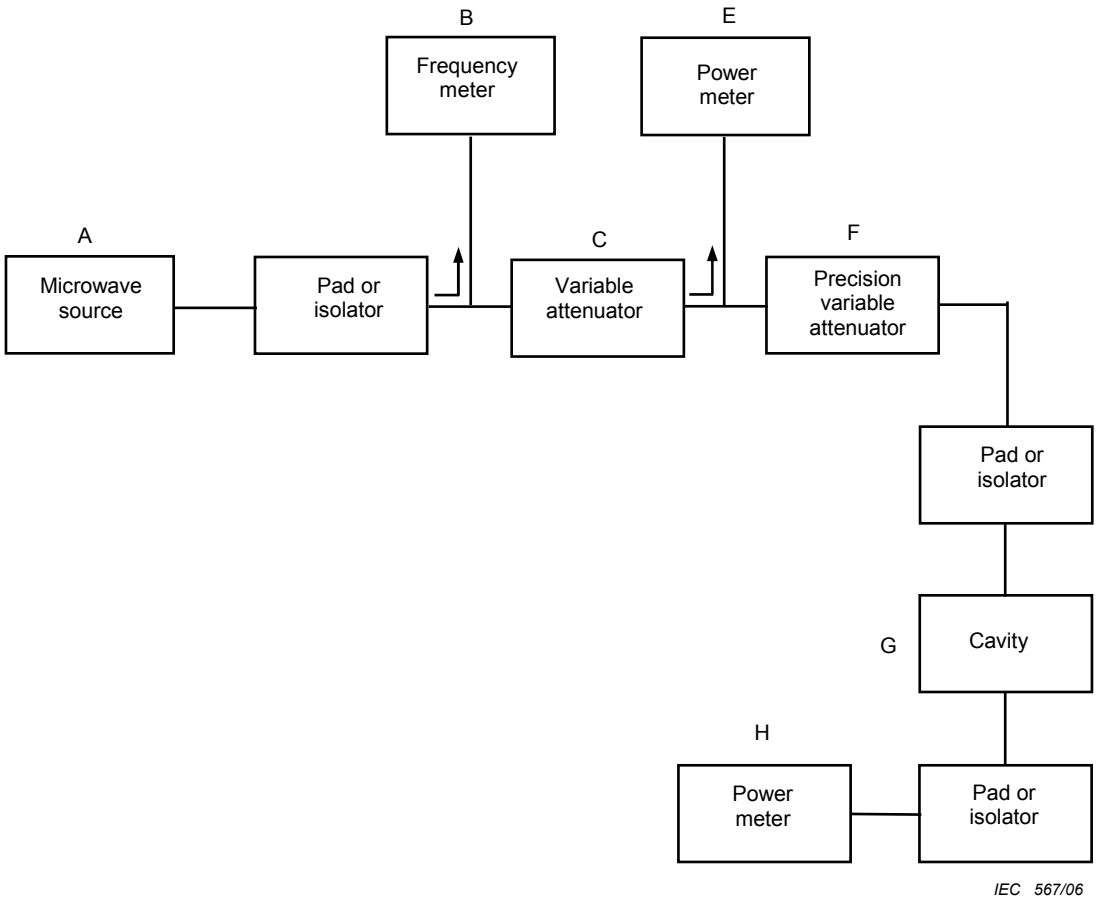

Figure 13 – Schematic diagram of the equipment required for measurement of gyromagnetic resonance linewidth and effective Landé factor

The gyromagnetic resonance linewidth may now be obtained by the following method:

Method

Calculate the attenuator setting to obtain the reference output level at the half-power points with the aid of equation (28). Set the precision attenuator at this value and vary the magnetic field to obtain the reference output level. Retune the cavity for maximum output with the aid of the tuning rod. Readjust the field strength and the tuning as required and note the final field strength value H_1. Repeat the procedure at the other half-power point to obtain H_2.

In order to check sphericity and isotropy of spherical specimens, the specimen may be rotated in the cavity. The values obtained for H_0 and ΔH should not depend upon the specimen orientation for correctly shaped isotropic materials. Allowable limits of variation are 1 % of H_0 and 5 % of ΔH. For thin disk specimens, the effect of the electromagnetic mirror image upon the measured data shall be eliminated prior to final measurement. This is effectively accomplished by making successive measurements on a specimen whose thickness is varied stepwise by means of careful grinding[3]. The values obtained for H_0 and ΔH should not depend upon the thickness. Allowable limits of variation are in this case 3 % of H_0 and 5 % of ΔH.

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3 In most practical cases this condition is reached for a given material with a particular value of the ratio $\rho = d/D$, which may be determined from the result of the procedure described. Usually $\rho < 1/10$.

6.7 Calculation

The effective Landé factor is calculated from observed values of frequency and resonance field strength according to equation (26) (sphere) or equation (27) (disk).

The gyromagnetic resonance linewidth is calculated as

$$\Delta H = \left| H_1 - H_2 \right| \tag{31}$$

6.8 Accuracy

If frequency is measured with an accuracy of ± 1 % and magnetic field strength with an accuracy of ±2 %, the relative errors in the determination of ΔH and g_{eff} become equal to ±5 % and ±2 %, respectively.

6.9 Data presentation

Data shall be presented so as to conform with the requirements of IEC 60392. The measurement frequency shall be declared: this may be done by using a subscript which represents the measuring frequency in gigahertz, i.e. ΔH_{10}, g_{10} (if measured at 10 GHz). Information on the shape and size of the specimen (spherical or disk-shaped, dimensions) is desirable, and its unique identity shall be given.

7 Gyromagnetic resonance linewidth ΔH_{10} and effective Landé factor g_{10} (at 10 GHz)

7.1 General

Gyromagnetic resonance is characterized by an effective Landé factor and a resonance linewidth. The measurement of these quantities involves both frequency and applied magnetostatic field as critical parameters.

Stability, both dimensional (of the cavity) and electrical, thus becomes of primary importance, particularly with regard to materials having very narrow resonance linewidths.

7.2 Object

To describe a method for measuring gyromagnetic resonance linewidth and effective Landé factor of isotropic microwave ferrites at a frequency of 10 GHz. It may be used for materials having wide as well as narrow linewidths.

7.3 Theory

The method applies exclusively to the uniform precession resonance; such resonances in which magnetostatic modes of higher order are involved or which suffer from ambiguity due to insufficient magnetic saturation are disregarded.

The value of the field for maximum absorption or resonance may be theoretically computed in terms of the magnetization of the sample, the demagnetizing factor, the effective Landé factor g_{eff} and the measuring frequency f_0. If the specimen has the shape of a small sphere the relationship reduces to the simple formula:

$$f_0 = \frac{\gamma \mu_0 H_0}{2\pi} \tag{32}$$

where

γ is the gyromagnetic ratio;

μ_0 is the magnetic constant.

Recognizing that γ = 88 $g_{\text{eff}} \cdot 10^9$ T^{-1} s^{-1}, it is thus possible, knowing f_0 and H_0 to calculate the effective Landé factor g_{eff} which may depend on H_0.

The gyromagnetic resonance linewidth ΔH is defined as the difference between the two magnetic field strength values at which the power absorbed by the ferrite material is one-half the maximum absorption.

The method recommended for the measurement of g_{eff} and ΔH is based on the cavity perturbation theory. The absorption at resonance is approximately proportional to the (saturation) magnetization divided by the resonance linewidth. If the absorption becomes too large to maintain the required accuracy, as may sometimes be the case with narrow linewidth materials, the specimen should be reduced in size. To obtain less absorption, the diameter (of spherical samples) should be reduced as required (see 7.4).

The absorption in the specimen is measured by determining the change of power incident on the cavity required to keep the output power from the cavity at a fixed reference level.

The variation in input power may be expressed as the variation of attenuation inserted between the monitored source and the cavity in order to maintain the reference or input level. If α_0 is the attenuator reading in decibels with no sample present and α_{r} is the reading for maximum specimen absorption, then the reading $\alpha_{1/2}$ corresponding to a specimen absorption of half the resonance value, is given by one of the following equations:

$$\alpha_{1/2} = \alpha_0 + 10 \lg 2 - 10 \lg \left(10^{(\alpha_0 - \alpha_{\text{r}})/10} + 1\right) \tag{33}$$

7.4 Test specimen and cavity

The test specimen for this method is a sphere. Spherical specimens with a diameter not greater than 1 mm will give sufficient accuracy, provided that ΔH is greater than approximately 800 Am^{-1}. When ΔH is less than 800 Am^{-1} and particularly when the magnetization is high, a smaller sphere will be required. This is found out by verifying whether the condition:

$$\alpha_0 - \alpha_{\text{r}} < 20 \lg \left(1 + 0{,}06\, \text{Q}_0 \frac{\Delta H}{H_0}\right) \tag{34}$$

is met, where Q_0 is the Q value of the cavity without specimen.

The cavity is of the transmission type, resonant at 10 GHz with a loaded Q (Q_0) greater than 2 000. The specimen is positioned away from the cavity walls at a point of minimum electric and maximum magnetic microwave field. Figure 11 with the dimensions for f = 10 GHz, shows a suitable cavity in which the proper specimen position is indicated. The specimen is mounted on a fused silica (or other dielectric) rod. The hole for inserting the specimen into the cavity is located in the narrow cavity wall and shall not exceed 2 mm in diameter. An additional perturbing rod is mounted in a suitable position to allow tuning by interaction with the electric field in the cavity. The input and output lines to the cavity are made to appear as matched loads by means of pads or isolators. This cavity design applies for spherical samples, having diameters restricted according to the preceding paragraph at a measuring frequency of 10 GHz.

7.5 Measuring apparatus

Figure 14 is a schematic diagram of the equipment required to make the measurements. Power from a suitable microwave source A, operated either unmodulated or with amplitude modulation, but free from frequency modulation, is fed through a precision variable attenuator F to the cavity G, and the output power is detected and indicated on a suitable meter H. The power incident on the precision attenuator is monitored at E by means of a directional coupler and crystal detector, and this incident power is kept constant throughout the measurement by means of a variable attenuator C. The microwave frequency, which is monitored at B, can be kept unchanged because the perturbing rod may be used to tune the cavity to the generator frequency. An adjustable magnetic field of sufficient stability perpendicular to the microwave magnetic field is applied to the specimen. The inhomogeneity of the applied field over the specimen shall be negligible compared to the linewidth being measured.

7.6 Measuring procedure

Set the generator frequency as closely as possible to 10 GHz. Tune the cavity for maximum transmission with the aid of the dielectric rod. Establish an input level measured at E, a setting α_0 on the precision attenuator, and an output level measured at H. Take this output level as reference value.

Insert the specimen into the cavity. This operation should have negligible effect on the output level. Apply the magnetic field and adjust it for maximum absorption (minimum transmission). Determine the new setting α_r on the precision attenuator which restores the output level to the reference value. Determine the microwave frequency f_0 and the applied magnetostatic field strength H_0.

The gyromagnetic resonance linewidth may now be obtained by the following method:

Method

Calculate the attenuator setting to obtain the reference output level at the half-power points with the aid of equation (33). Set the precision attenuator at this value and vary the magnetic field to obtain the reference output level. Retune the cavity for maximum output with the aid of the dielectric rod. Readjust the field strength and the tuning as required and note the final field strength value H_1. Repeat the procedure at the other half-power point to obtain H_2.

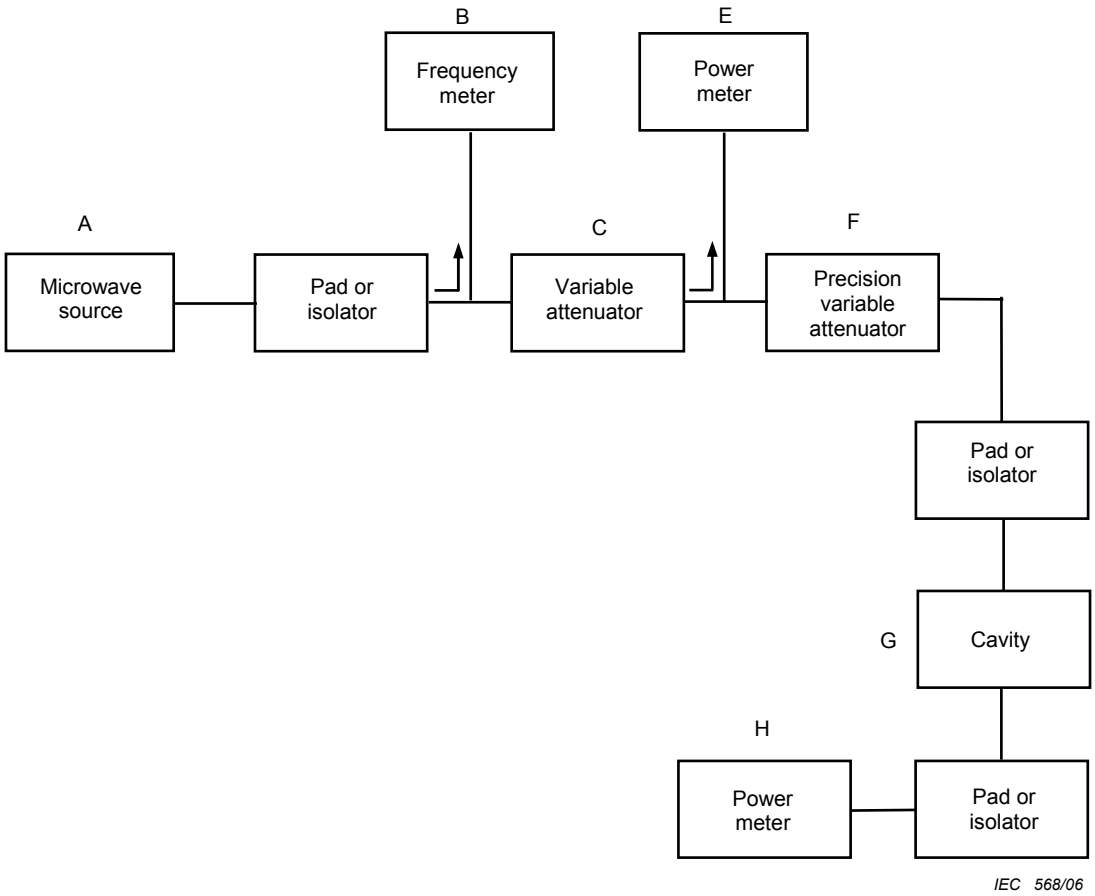


Figure 14 – Schematic diagram of the equipment required for measurement of gyromagnetic resonance linewidth and effective Landé factor at 10 GHz

In order to check sphericity and isotropy of the specimen, the sphere may be rotated in the cavity. The values of field strength measured should not depend upon specimen orientation for correctly shaped isotropic materials. A variation of ±1 % due to rotation may, however, be tolerated.

7.7 Calculation

The effective Landé factor is calculated from known values of frequency and resonance field strength according to equation (32).

The gyromagnetic resonance linewidth is calculated as

$$\Delta H = \left| H_1 - H_2 \right| \tag{35}$$

7.8 Accuracy

If frequency is measured with an accuracy of ±1 % and magnetic field strength with an accuracy of ±2 %, the relative errors in the determination of ΔH and g_{eff} become equal to ±5 % and ±2 %, respectively.

7.9 Data presentation

The values obtained shall be expressed as follows:

– resonance linewidth at 10 GHz, ΔH_{10} at a temperature of θ °C: p kAm^{-1} ± 5 %;

– effective Landé factor at 10 GHz, g_{10}, at a temperature of θ °C: q ± 2 %.

where the numbers p and q are given to three significant figures.

The report shall also include the unique identity of the sample.

8 Spin-wave resonance linewidth ΔH_k

8.1 General

Ferrite materials exhibit an anomalous absorption at high r.f. power levels that results from a power dependent coupling between the uniform mode of precession and spin-waves, or through a direct coupling of r.f. field to spin-waves. Through this transfer of energy, certain spin-wave amplitudes build up. The spin-wave frequencies are equal to one-half the applied frequency or to the applied frequency. The absorption is observed when the spin-waves are parametrically excited beyond some threshold level where unstable growth of spin-wave amplitude occurs. This threshold level, and hence the relatively high power performance of the ferrite material, can be shown to be related to the spin-wave linewidth ΔH_k of the material.

Spin-wave linewidth is an important property of the material, and its determination is necessary to characterize the material completely. Not only do the high-power characteristics of the materials depend on ΔH_k but this linewidth is also indicative of loss in applications where the material is biased far from resonance. For information about spin-waves in general and, in particular, about their significance in microwave ferrite applications, see [7] and [8].

8.2 Object

The procedure described permits the determination of the microwave spin-wave linewidth of gyromagnetic materials. The test is made at frequencies near to 10 GHz, on spherical samples at room temperature. Both mono- and polycrystalline samples can be measured by this procedure. In the case of monocrystalline samples, account shall be taken of the orientation of the crystal.

The measurement described here is based on the so-called parallel pump technique wherein the sample is biased below resonance by a magnetostatic field applied parallel to the r.f. field. In this arrangement, the sample shows low magnetic loss at low r.f. power levels. The threshold r.f. field is determined by observing the onset of non-linear loss as evidenced by a change in shape of the r.f. pulse. Although most devices operate with perpendicular high-frequency and magnetostatic fields, this method, employing parallel pumping for convenience, nevertheless gives results indicative of the losses at high-power levels.

For materials having a large ΔH_k (of the order of 1 kAm^{-1}), the onset of pulse deterioration may be difficult to observe, making measurement of μ'' as a function of power a preferable method [7], where μ'' is the imaginary part of the complex permeability.

8.3 Theory

The excitation of spin-waves beyond the threshold level is observed either as an increase in loss at magnetostatic field values below that required for resonance or as a saturation and broadening of the main resonance line. These effects are indicated in Figure 15. Because the subsidiary resonance exhibits a more sharply defined threshold, more accurate measurements of threshold level are possible in that region.

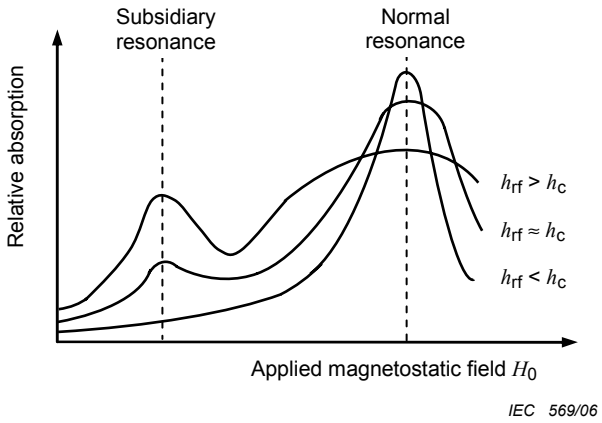


Figure 15 – Subsidiary absorption and saturation of the normal resonance

With an increasing r.f. field, high power absorption is first observed at the trailing edge of the r.f. pulse. As the r.f. field is increased beyond this threshold, absorption occurs over increasingly larger fractions of the pulse as indicated in Figure 16.

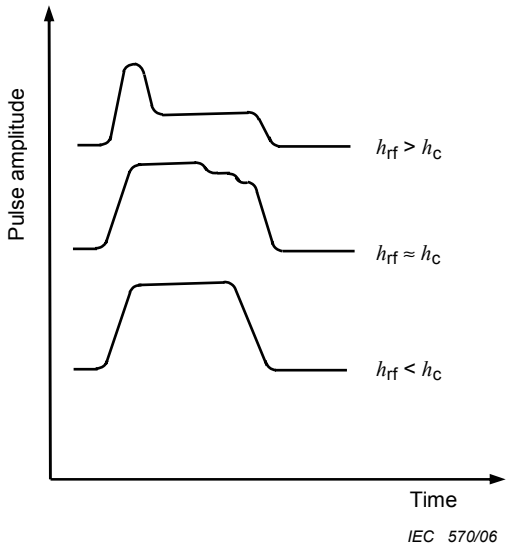


Figure 16 – Pulse deterioration at onset of subsidiary resonance

This behaviour is a result of the time required for the spin-wave amplitude to build up and can lead to some ambiguity in critical field determination h. It is experimentally found that measured critical field values are a function of t_d, where t_d is the pulse duration. Optimally, the measurements should be made with a pulse whose duration is long compared to the time required for spin-wave build-up at threshold. For polycrystalline materials with ΔH_k > 800 Am^{-1}, a pulse length of 1 μs is adequate, but for materials with ΔH_k < 800 Am^{-1}, a longer pulse length is necessary. Equipment limitations may make this impossible and, as an alternative, measurements of h can be made at different pulse lengths and extrapolated as indicated in Figure 17 to obtain the true value.

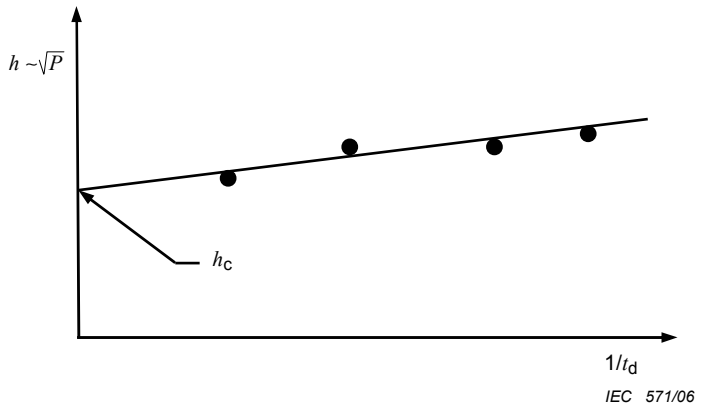


Figure 17 – Measured critical r.f. field strength as a function of pulse duration t_d

The threshold field strength h_c is equal to the r.f. magnetic field strength at the sample at the critical power level. When the sample is located at the centre of a TE_{10n} cavity (where n is even), the r.f. field strength is given by

$$h_{rf} = 4\sqrt{\frac{P_{in} \cdot Q_L}{s \cdot \mu_0 \pi f_0 \cdot abd\left[1+(d/na)^2\right]}} \tag{36}$$

where

s is 1 + γ_1 (subcritical coupling);

s is 1 + (1/γ_1) (overcritical coupling);

γ_1 is the input VSWR of cavity at resonance;

P_{in} is the peak power incident at resonance;

Q_L is the loaded Q of the cavity;

a, b, d are the cavity width, height and length, respectively;

f_0 is the resonant frequency of the cavity;

μ_0 is the magnetic constant;

n is the number of half-wavelengths along the cavity.

From this threshold field strength, the spin-wave linewidth ΔH_k in the general case can be calculated from the formula:

$$\Delta H_k = h_c \cdot \frac{\omega_m}{\omega} \cdot \sin^2\theta_k \tag{37}$$

where θ_k is the angle between the spin wave propagation direction and the direction of the magnetostatic field, and ω, ω_m have the meanings given below.

The lowest value of h_c is obtained when $\theta_k = \pi/2$, in which case:

$$\Delta H_k = h_c \cdot \frac{\omega_m}{\omega} \tag{38}$$

where

ω_m is $\gamma\mu_0 M_s$;

γ is the gyromagnetic ratio;

M_s is the saturation magnetization;

ω is the operating angular frequency.

In the case of monocrystalline samples, ω_m shall be corrected with regard to anisotropy.

The minimum threshold for parallel pumping occurs when spin-waves with $\theta_k = \pi/2$ are degenerated with one-half of the operating frequency, and, in the case of a sphere, this occurs at an applied magnetostatic field strength H_0, given by

$$H_0 \approx -\frac{M_s}{6} + \frac{1}{2}\sqrt{M_s^2 + \left(\frac{\omega}{\gamma \mu_0}\right)^2} \qquad (39)$$

8.4 Test specimen and cavity

The sample to be measured shall be spherical and have a diameter between 1 mm and 2 mm. A transmission cavity of the type sketched in Figure 18 can be conveniently used as a TE_{104} cavity resonant between 9 GHz and 10 GHz with a loaded Q of between 2 000 and 3 000. The sample is mounted on a rod of fused silica or other suitable dielectric, and positioned in the centre of the cavity cross-section at a point of minimum r.f. electric field and maximum r.f. magnetic field. The hole for inserting the sample into the cavity is centred in the broad wall of the cavity.

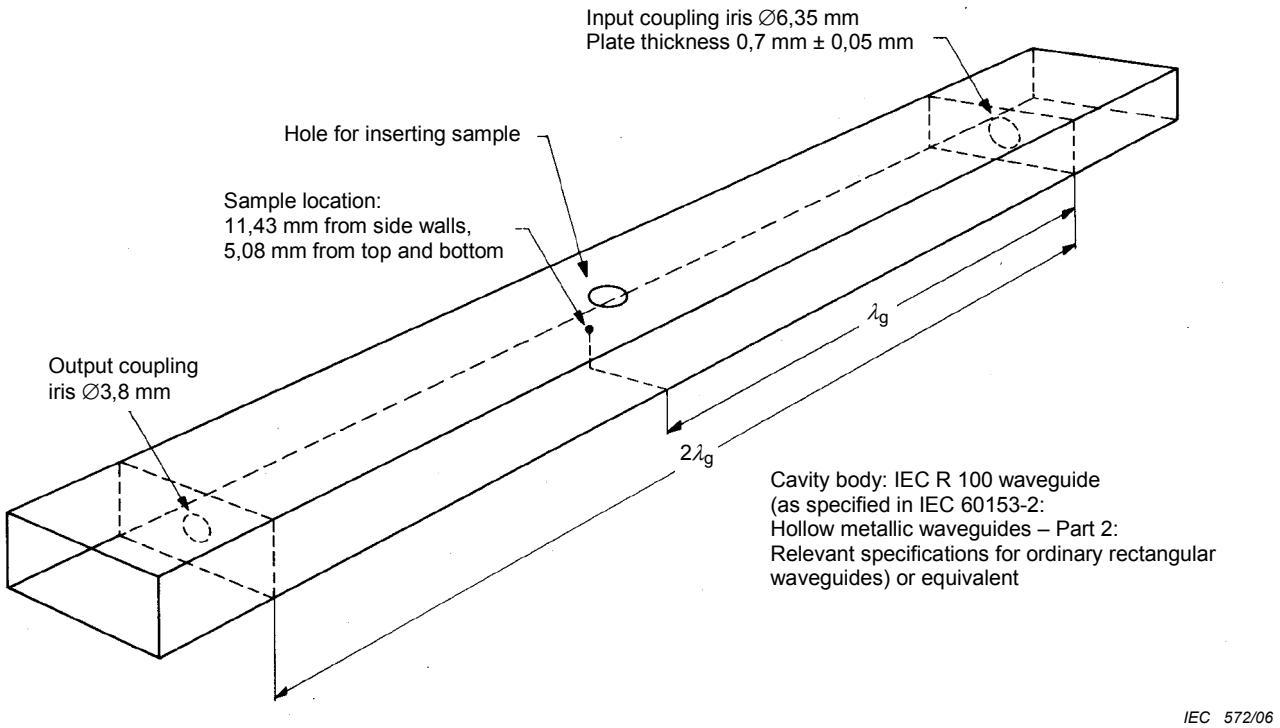


Figure 18 – Typical TE_{104} cavity for the measurement of spin-wave resonance linewidth at about 9,3 GHz

8.5 Measuring apparatus

Figure 19 is a block diagram of the equipment required. The pulse modulator A operates the magnetron B at a duty cycle of about 10^{-4} and provides a synchronizing pulse to the oscilloscope L. The isolator C provides an impedance matched to the magnetron and the power divider D allows the power to the test cavity F to be varied over at least a 20 dB range. The unused power is dissipated in the high-power termination E. The frequency and power level incident on the test cavity are monitored by the frequency meter H and the peak power meter I. This monitoring is accomplished with a directional coupler whose directivity exceeds 40 dB. The power reflected from the cavity at resonance is monitored through an identical coupler by the peak power meter G. By comparing the readings of meters G and I, the power reflection coefficient Γ can be obtained and the input voltage standing wave ratio γ_1 computed. The transmitted signal is terminated in a high-power termination J, sampled through a directional coupler by a crystal detector K and displayed on the oscilloscope L.

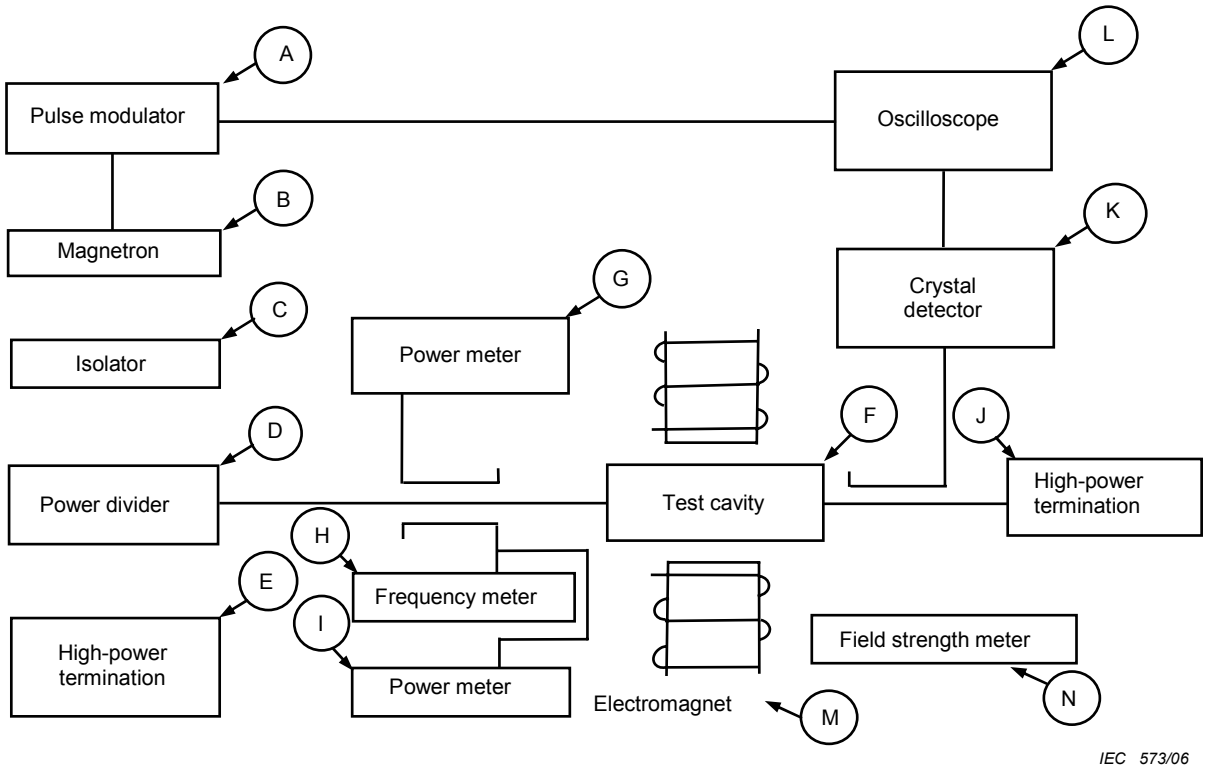


Figure 19 – Block diagram of spin-wave resonance linewidth test equipment

8.6 Calibration

The loaded Q of the cavity shall be determined. This can be easily accomplished with the equipment and procedures used to determine the complex permittivity of ferrite materials (see Clause 10).

8.7 Measuring procedure

The sample to be measured is mounted in the cavity and the field supplied by the electromagnet M is adjusted with the aid of the field strength meter N to provide a magnetostatic field strength approximately equal to that calculated from equation (39). This field shall be oriented in a plane parallel to the broad wall of the waveguide and normal to the longitudinal axis of the guide, i.e. parallel to the r.f. magnetic field in the guide at the sample location.

The frequency of the magnetron is made to coincide with the resonant frequency of the cavity by adjusting the frequency for maximum output of the crystal detector K. The pulse duration shall be made as long as possible and the repetition rate adjusted to yield a duty cycle of the order of 10^{-4}. With the magnetron operating at the resonant frequency of the cavity, the power reflection coefficient can be determined from readings at meters G and I.

The power divider is adjusted so that the r.f. magnetic field in the cavity according to equation (36) is well below the critical value and then increased until some deterioration of pulse shape is observed. The magnetostatic field is then carefully adjusted about the determined value H_0 to minimize the critical field strength. The incident power level that first causes a perceptible degradation in shape of the trailing edge of the pulse can then be used to calculate the critical r.f. power level for that pulse length.

When necessary, as indicated in 8.3, the measurement should be repeated for shorter pulse lengths to establish a basis for extrapolation to infinite pulse length.

8.8 Calculation

From the value of h_c, the spin-wave linewidth ΔH_k is calculated from equation (38).

8.9 Accuracy

The determination of the quality factor of the loaded cavity Q_L shall be made to an accuracy of ±3 %. Incident power level determination shall be made to an accuracy of ±10 %. Cavity dimensions and resonant frequency measurements are easily made to within ±0,5 %. This restricts the expected error in ΔH_k to ±15 %.

The measurement technique described here is primarily intended for the evaluation of those ferrimagnetic garnets and spinels currently manufactured for use in microwave ferrite devices. Accuracy can be improved by employing reflection cavity techniques.

8.10 Data presentation

The value of ΔH_k shall be reported together with the frequency and temperature at which the measurements were made and the unique identity of the sample. The estimated accuracy of the measurement shall also be given.

9 Effective linewidth ΔH_{eff}

9.1 General

At magnetostatic field strengths widely different from that required for resonance at the working frequency, calculation of the permeability tensor components using the gyromagnetic resonance linewidth ΔH yields results which can be grossly in error. Consequently, insertion loss values cannot be predicted with sufficient accuracy. In order to eliminate this difficulty an effective linewidth ΔH_{eff} is defined, which takes into account any deviations from the classical Lorentzian behaviour. In this context, effective linewidth means the relaxation parameter W as given in [9] . Knowledge of the related frequency shift S is also required to make a formal calculation of the imaginary part μ''_+ of the permeability for the clockwise sense of circular polarization.

9.2 Object

This method covers the measurement of the magnetic permeability tensor components from which the effective linewidth is deduced. The method is valid for magnetically saturated polycrystalline isotropic ferrites operating at microwave frequencies, outside the gyromagnetic resonance region and at low power level. The test specimen is a rod, arranged coaxially in a resonant cylindrical cavity and submitted to an axial magnetostatic field. The effective linewidth is a useful parameter as regards the insertion loss of microwave devices.

9.3 Theory

9.3.1 Definitions

In an isotropic magnetic medium, submitted to a magnetostatic field H_0, the microwave magnetic flux density B is related to the microwave magnetic field strength H by the following equation:

$$B = \mu_0(\mu)H = \mu_0(1+\kappa)H \tag{40}$$

where

μ_0 is the magnetic constant;

(μ) is the relative tensor permeability of the medium;

(κ) is the relative tensor susceptibility of the medium;

(μ) and (κ) are functions of H_0.

In perpendicular pumping, the susceptibility tensor may be reduced to a two-dimensional expression:

$$(\kappa) = \begin{pmatrix} \kappa_+ & 0 \\ 0 & \kappa_- \end{pmatrix} \tag{41}$$

where κ_+ and κ_- are the susceptibilities for the clockwise and counter-clockwise circularly polarized waves, respectively. Usually, they are complex quantities:

$$\kappa_\pm = \kappa'_\pm - \mathrm{j}\kappa''_\pm \tag{42}$$

the imaginary part κ'' originating from the magnetic losses in the medium, and being related to the effective linewidth ΔH_{eff}.

$$\Delta H_{\mathrm{eff}} = 2M_{\mathrm{s}} \cdot Im\left(\frac{1}{\kappa_+}\right) \tag{43}$$

where M_{s} is the saturation magnetization. However, these susceptibilities $k_\pm$ are intrinsic susceptibilities of the medium. Due to demagnetizing effects, the quantities obtained through measurement in a cavity are effective susceptibilities:

$$\kappa_{\pm\mathrm{e}} = \kappa'_{\pm\mathrm{e}} - \mathrm{j}\kappa''_{\pm\mathrm{e}} \tag{44}$$

Since $Im\left(\frac{1}{\kappa_{+\mathrm{e}}}\right)$ is equal to $Im\left(\frac{1}{\kappa_+}\right)$, independent of the demagnetizing factor N, ΔH_{eff} may then be rewritten:

$$\Delta H_{\mathrm{eff}} = 2M_{\mathrm{s}} \cdot Im\left(\frac{1}{\kappa_{+\mathrm{e}}}\right) = 2M_{\mathrm{s}} \frac{\kappa''_{+\mathrm{e}}}{(\kappa'_{+\mathrm{e}})^2 + (\kappa''_{+\mathrm{e}})^2} \tag{45}$$

9.3.2 Measurement

A cylindrical TM_{110} resonator and a rod-shaped specimen are used for the measurement (see Figures 20 and 21).

With the applied magnetic field H_0 and for a circular polarization in the clockwise sense of the microwave magnetic field, the following quantities shall be measured: the resonant frequency of the cavity with and without the specimen, the loaded Q of the cavity with the specimen and the sufficiently magnetically saturated specimen, and the dimensions of the cavity and the specimen.

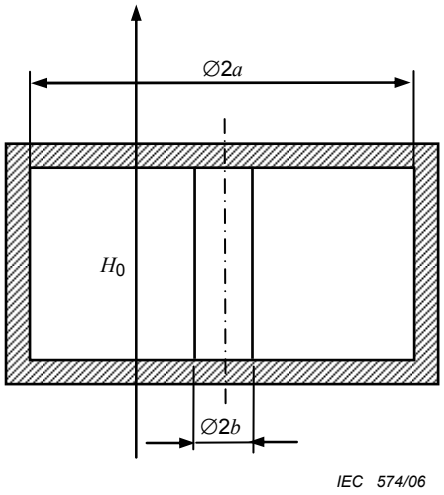


Figure 20 – Sectional view of the cavity with specimen

If f_0 is the resonance frequency of the empty cavity and $f = f_0 + \delta f_+$ is that of the cavity containing the specimen, κ'_{+e} and κ''_{+e} may be expressed as functions of $\delta f_+/f_0$ by an approximation, according to [10], as follows:

Dimensions in millimetres

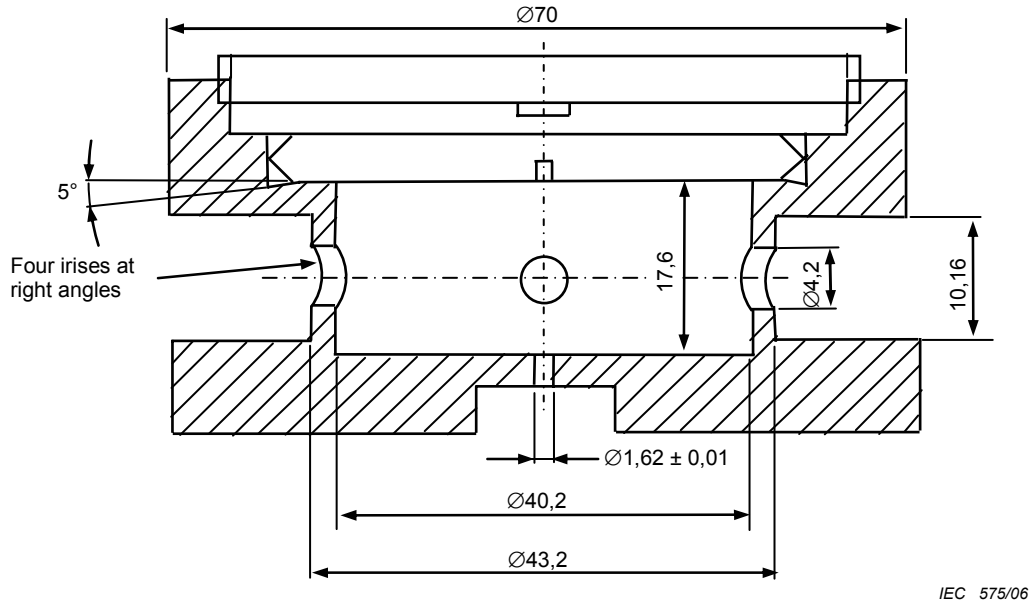


Figure 21 – Dimensions of a cavity designed for resonance at a frequency of 9,1 GHz

With the cavity dimensions given in Figure 21, and using the following designations:

a is the radius of the cavity, determined from the resonance frequency of the empty cavity;

b is the radius of the specimen;

ε' is the real part of the relative permittivity of the specimen;

ε'' is the imaginary part of the relative permittivity of the specimen;

Q_+ is the loaded Q of the cavity with the specimen to be measured;

Q_0 is the loaded Q of the cavity with the saturated low-loss sample.

The following parameters are defined:

$$C_1 = \left(\frac{b}{a}\right)^2 \left(1 + \frac{2\delta f_+}{f_0}\right)$$

$$C_2 = \frac{\varepsilon'}{2}\left(1 + \frac{1}{1+\kappa'_{+e}}\right) - 1$$

$$C_3 = \frac{1}{4}\left(1 - \frac{1}{\left(1+\kappa'_{+e}\right)^2}\right)$$

$$C_4 = \left[1 - 1{,}191\frac{\delta f_+}{f_0}\left(\frac{1}{3{,}671\,C_1} + 1 - 4{,}605 \lg 3{,}415\,\frac{b}{a}\right)\right]^2$$

The susceptibility components are then given approximately by

$$\frac{1}{1+\kappa'_{+e}} = 3{,}671\varepsilon' C_1 - 1 + 2\left[\frac{1 + 5{,}485(\delta f_+ / f_0)\lg 3{,}415(b/q)}{C_4^{1/2}}\right] \tag{46}$$

$$\frac{\kappa''_{+e}}{(1+\kappa'_{+e})^2} + 3{,}671\varepsilon'' C_1 = 2\left(\frac{1}{Q_+} - \frac{1}{Q_0}\right)\left(\frac{1}{6{,}153 C_1 C_4} + 3{,}671\,C_1 C_2 + C_3\right) \tag{47}$$

An alternative approximation may be developed by means of a computer programme on complex Bessel functions.

9.4 Test specimen and cavity

The specimen shall be cylindrical, of diameter (1,60 ± 0,01) mm and of length (22 ± 0,5) mm. It shall be in a clean and dry state. The test specimen is inserted through holes in the cavity wall and a uniform axial magnetic field is imposed on the specimen.

The dimensions of the cavity are given in Figure 21. It has four irises at right angles, two of them for excitation of the circularly polarized wave, and two for detection.

The coupling coefficient is identical for each iris and less than 0,1. The loaded Q of the cavity shall be greater than 5 000.

The preparative process may introduce stress in the specimen affecting the measured value of ΔH_{eff}. This effect may be minimized by a process of annealing for a short period of time.

9.5 Measuring apparatus

Figure 22 is a schematic diagram of the equipment required for the measurement. Power from either an X-band sweep generator, SG, or a high-stability X-band CW generator, G (short-term stability better than 1×10^{-7}) is fed through a variable attenuator A, the frequency being measured by F, then through a variable precision attenuator V, power being measured at P.

A magic tee divides the power into two parts which, through adjustments of the variable attenuators A_1 and A'_1 and the variable phase shifter D_1, recombine to give a circularly polarized wave inside the cavity C. The two output irises, through adjustments of the variable attenuators A_2 and A'_2 and the variable phase shifter D_2, feed a magic tee delivering output power to detectors E and H. The boxes I are isolators. The axial magnetostatic field H_0 is measured with a field strength meter M.

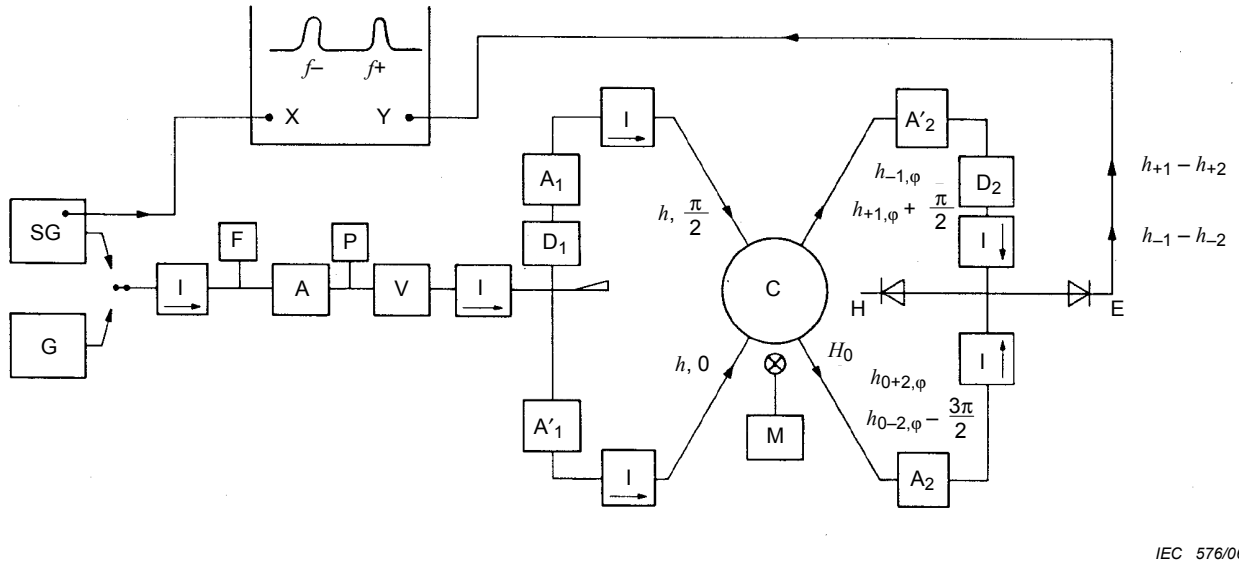


Figure 22 – Schematic diagram of equipment for measuring effective linewidth ΔH_{eff}

9.6 Calibration

The frequency meter, the variable precision attenuator and the field strength meter shall be calibrated.

9.7 Apparatus adjustment

Since the measurement depends upon the precise detection of small quantities, it is important that complete temperature stabilization is achieved before any adjustment of the apparatus is made, and that it is maintained throughout the entire measurement.

9.7.1 Adjustment principle

An empty, perfect TM_{110} cavity, excited by a linearly polarized wave, provides two degenerate contra-rotating modes. Due to unavoidable mechanical imperfections, the modes are slightly separated. Let f_+ be the clockwise mode frequency and f_- the counter-clockwise mode frequency.

If a ferrite cylinder is inserted into the cavity and an axial magnetic field H_0 is applied, the two mode frequencies are separated according to the difference between μ_+ and μ_-. When H_0 becomes very high, μ_+ and μ_- tend to unity and the difference $f_+ - f_-$ tends to zero.

The purpose of the measuring equipment described above is to obtain the rotating mode f_+. By means of the input magic tee, attenuators and phase shifter, two signals in phase-quadrature are applied to the input irises of the cavity. The phase shift between the signals at the output irises is compensated by the output phase shifter so that the signals are in phase again.

After some amplitude correction, the signals are recombined in the output magic tee; their sum at the H arm gives the f_+ signal; their difference at the E arm gives a null. However, if the phase and amplitude adjustments are not correct at the cavity input, the f_- mode is detected. At the output irises, the f_- signals are in phase quadrature, but after the additional $\pi/2$ phase shift they become in antiphase. The f_- signal therefore appears in the E arm of the magic tee.

The equipment is aligned by adjusting phase and amplitude of the input and output signals to obtain a null at the E arm, for f_- and f_+ respectively.

9.7.2 Adjustment procedure

Reset to zero all attenuators and phase shifters. Connect generator SG and switch the oscilloscope to the E arm of the output magic tee. Insert the specimen into the cavity and apply the desired value of the magnetic field H_0. Two peaks appear on the oscilloscope screen. As H_0 is varied, only the f_+ peak moves and the f_- peak remains stationary.

First use phase shifters D_1 and D_2 to reduce the intensity of the f_- and f_+ peaks. D_1 mainly controls the f_- peak and D_2 the f_+ peak. Then obtain a minimum for the f_- peak by successive adjustments of A_1 (or A'_1) and D_1.

Similarly, obtain a minimum for the f_+ peak by successive adjustments of A_2 (or A'_2) and D_2.

Check that, at the H arm, only the f_+ peak appears and is about 40 dB above the residual peaks at the E arm.

This adjustment shall be repeated for each specimen and for each value of the applied magnetostatic field strength.

9.8 Measuring procedure

9.8.1 Measurement of f_0

Connect generator SG, insert the low-loss sample in the cavity and apply the maximum value of the magnetostatic field strength. Adjust as specified in 9.7.2.

Using D_1 and D_2 increase the f_+ peak at the E arm by about 20 dB.

Switch off the magnetostatic field and remove the low-loss sample: then the larger peak detected at the E arm corresponds to f_0. By means of the phase shifters and attenuators, cancel the f_- peak.

Connect generator G and measure the frequency f_0.

The radius of the cavity is calculated from f_0 by means of the expression:

$$a = 3{,}8317 \cdot \frac{c}{2\pi f_0} \tag{48}$$

where c is the speed of light.

9.8.2 Determination of Q_0

Q_0 is extrapolated from measurements made on the low-loss sample at different high values of the applied magnetostatic field strength.

Insert the low-loss sample and apply a known value of the applied magnetostatic field strength H_0. After adjustment, as specified in 9.7.2, connect generator G.

Introduce an attenuation of 3 dB with the variable precision attenuator V. Adjust the microwave frequency to cavity resonance as indicated by maximum output power with respect to frequency variation. Note the indication of the output power level on the H arm and measure the resonance frequency f with the frequency meter F. Remove the 3 dB of attenuation on V and locate the two frequencies at which the output power is the same as at cavity resonance with the 3 dB attenuation in. The frequency separation of the half-power points is measured on the frequency meter F as Δf. The loaded Q of the cavity with the low-loss sample at H_0 is given by

$$Q = \frac{f}{\Delta f} \tag{49}$$

Repeat the operation for increasing values of magnetostatic field strength. Draw the curve Q = $f/\Delta f$ versus H_0. The minimum of Q gives the resonance field strength H_r for the low-loss specimen.

Plot values of $1/Q = f/\Delta f$ versus $(H_0 - H_r)^{-2}$ and deduce Q_0 by extrapolation:

$$\frac{1}{Q_0} = \lim_{H_0 \to \infty} \frac{1}{Q} \tag{50}$$

as illustrated in Figure 23.

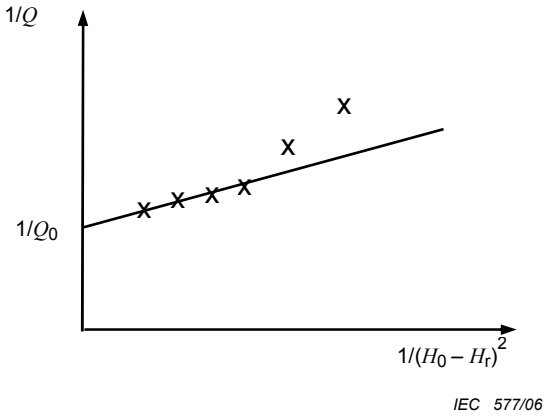


Figure 23 – Determination of Q_0

9.8.3 Measurement of f and Q

Insert the specimen to be measured in the cavity and apply the desired value of magnetostatic field strength H_0. Adjust as in 9.7.2.

Connect generator G and measure as specified in 9.8.2. Record f (= f_0 + δf_+) and Δf. Calculate Q_+(= $f/\Delta f$).

9.9 Calculation

κ'_{+e}, κ''_{+e} and ΔH_{eff} are calculated from the equations (45), (46) and (47), using values of ε' and ε'' measured separately. (A suitable measuring method is given in Clause 10.)

9.10 Accuracy

The overall accuracy in κ'_{+e} is of the order of 2 %.

The overall accuracy in ΔH_{eff} is ≈ 20 % (for low values: 80 Am^{-1} or 20 %, whichever is the greater).

9.11 Data presentation

The report shall include the following:

unique identity of the sample;

value of the magnetic field strength H_0;

value of κ'_{+e}, κ''_{+e} and ΔH_{eff}; and

temperature of the sample during the measurement.

The estimated accuracy of the measurements shall also be given.

10 Complex permittivity $\underline{\varepsilon}_r$

10.1 General

A knowledge of the complex permittivity of a ferrite material is of primary importance for the theoretical analysis of wave propagation in ferrites as well as in the design of ferrite microwave components. Microwave ferrites frequently exhibit very low dielectric loss, in fact so low that it becomes difficult to measure, primarily due to the fact that it becomes difficult to distinguish between dielectric and magnetic loss. This difficulty is often avoided by subjecting the test sample to a very strong magnetic field, so strong that it saturates the material and moves the gyromagnetic resonance frequency well above the measuring frequency. By this means neither low-field nor resonance magnetic losses will be present to obscure the result.

10.2 Object

To describe a method for the measurement of complex permittivity of isotropic ferrites for microwave applications by means of a resonant cavity. For this measurement a rod-shaped test specimen is placed coaxially in a cylindrical cavity with openings in the wall to accept the ends of the specimen (Figure 25). The theory on which this method is based is strictly valid only for the impracticable arrangement shown in Figure 24, with no openings in the wall of the cavity and no air-gap between the ends of the specimen and the cavity; hence, there will be a systematic error which can be only roughly estimated. However, as it is possible to keep the error approximately constant, it does not normally affect comparative measurements on different materials.

The cavity is designed for a measuring frequency of about 10 GHz, the actual value depending upon the characteristics of the specimen. This is, however, relatively unimportant, since the dielectric properties of ferrites change very slowly with frequency in the microwave region.

10.3 Theory

In an isotropic dielectric medium having an applied steady electric field strength E, the electric displacement D is given by the equation:

$$D = \varepsilon_r \varepsilon_0 E \tag{51}$$

where

ε_0 is the electric constant;

ε_r is the relative permittivity.

NOTE In accordance with usual engineering practice, the subscript r in the symbols ε_r, ε'_r and ε''_r, etc. and the underlining of $\underline{\varepsilon}$ to denote that it is a complex quantity are omitted from the following text.

If the medium is subjected to an alternating electric field, the electric displacement is not necessarily in phase with the field strength. This fact may be expressed mathematically by assuming that ε is a complex quantity. If we write $\varepsilon = \varepsilon' - j\varepsilon''$, the imaginary part ε'' can be taken to represent the dissipation in the medium.

A cylindrical TM_{010}-resonator and a rod-shaped specimen are used for the measurement. The quantities that shall be measured are the resonant frequency and loaded Q of the cavity with and without the specimen, and the cavity and specimen dimensions. The method is not suitable for materials with dissipation factors $\tan \delta = \varepsilon''/\varepsilon' > 0{,}1$:

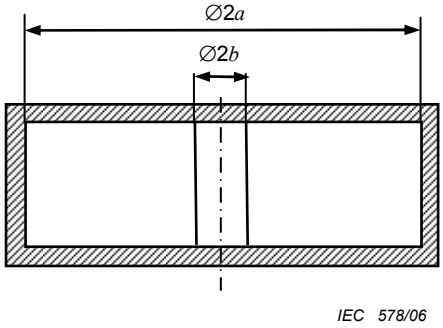


Figure 24 – Ideal resonant cavity with specimen, used for theoretical calculation (sectional view)

The cylindrical resonant cavity contains the coaxially mounted cylindrical specimen. The permeability of the specimen μ' is approximately equal to 1 and the real part of the permittivity ε' is determined by the equation:

$$\sqrt{\varepsilon'} \cdot \frac{J_1\left(\frac{\omega}{c}\varepsilon'^{1/2}b\right)}{J_0\left(\frac{\omega}{c}\varepsilon'^{1/2}b\right)} = \frac{J_1\left(\frac{\omega}{c}b\right)N_0\left(\frac{\omega}{c}a\right) - J_0\left(\frac{\omega}{c}a\right)N_1\left(\frac{\omega}{c}b\right)}{J_0\left(\frac{\omega}{c}b\right)N_0\left(\frac{\omega}{c}a\right) - J_0\left(\frac{\omega}{c}a\right)N_0\left(\frac{\omega}{c}b\right)} \tag{52}$$

J_0 and J_1 being the Bessel functions of order zero and one, N_0 and N_1 the Neumann functions of order zero and one, c the velocity of light in free space, a the radius of the cavity, b the radius of the specimen (Figure 24) and $\omega = 2\pi f$ the resonance angular frequency of the cavity.

By introducing f_0, the resonant frequency of the empty cavity, and f_1, that of the cavity containing the specimen, the series expansion of equation (52) in ascending powers of $\delta f / f_0 = (f_0 - f_1)/f_0$ and b/a results in the following approximation valid, for small values of these quantities [13]:

$$\varepsilon' = \varepsilon''\left(1 - 0{,}722\frac{b^2}{a^2}\bar{\varepsilon}'\right) \tag{53}$$

where

$$\bar{\varepsilon}' = 1 + \frac{0{,}78\frac{\delta f}{f_0}\left(1 + \frac{0{,}692\ a^2/b^2}{1 - 2\delta f/f_0}\right)}{1 + 1{,}56\frac{\delta f}{f_0}\ln\left(\frac{a/b}{2{,}14}\right)} \tag{54}$$

Assuming a specimen without loss ($\varepsilon'' = 0$), yet with the real part of ε remaining unaltered, the change in $1/Q$ when replacing the loss-free specimen by the real one is determined by the quotient of the following volume integrals [14] [15]:

$$\frac{1}{Q_1} - \frac{1}{Q_2} = \frac{\int_{V_s} \varepsilon'' |E|^2 \mathrm{d}V}{\int_{V_c} \varepsilon' |E|^2 \mathrm{d}V} \tag{55}$$

where

Q_2 is the loaded Q of the cavity with loss-free sample;

Q_1 is the loaded Q with real sample;

V_s is the volume of the sample;

V_c is the volume of the cavity with sample inserted;

E is the amplitude of the electric field with loss-free sample.

Using the same approximation as above, this results in:

$$\varepsilon'' = \left(\frac{1}{Q_1} - \frac{1}{Q_2}\right) = \left[\frac{0{,}27\, a^2/b^2}{\left(1 - \dfrac{\delta f}{f_0}\right)^2 \left(1 + 1{,}56 \dfrac{\delta f}{f_0} \ln \dfrac{a/b}{2{,}14}\right)^2} + \varepsilon' - 1\right] + \varepsilon' \left[\frac{1}{1 + 1{,}45 \varepsilon' b^2/a^2}\right] \tag{56}$$

With the dimensions of Figure 25, equations (53), (54) and (56) become:

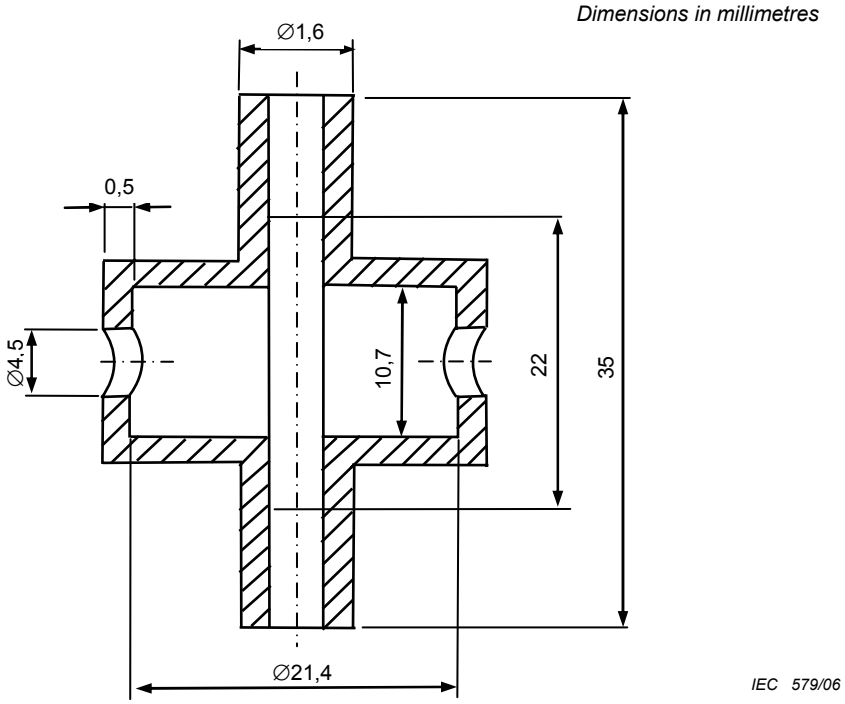
$$\varepsilon' = \bar{\varepsilon}' \left(1 - 4{,}0 \times 10^{-3} \varepsilon'\right) \tag{57}$$

$$\bar{\varepsilon}' = 1 + \frac{\dfrac{\delta f}{f_0}\left(0{,}78 + \dfrac{96{,}7}{1 - 2\,\delta f/f_0}\right)}{1 + 2\,,86\,\delta f/f_0} \tag{58}$$

and

$$\varepsilon'' = \left(\frac{1}{Q_1} - \frac{1}{Q_2}\right) = \left[\frac{48{,}1}{\left(1 - \dfrac{\delta f}{f_0}\right)^2 \left(1 + 2{,}86 \dfrac{\delta f}{f_0}\right)^2} + \varepsilon' - 1\right] \left[\frac{1}{1 + 0{,}0081\, \varepsilon'}\right] \tag{59}$$

where $Q_2 = Q_0 \left(1 + 0{,}65 \dfrac{\delta f}{f_0}\right)$ according to reference [1], Q_0 being the loaded Q of the empty cavity.



NOTE The resonant frequency of the empty cavity is 10,7 GHz [13].

Figure 25 – Dimensions of the resonant cavity with specimen

10.4 Test specimen and cavity

The specimen shall be cylindrical, with a diameter of (1,60 ± 0,01) mm and a length of (22 ± 0,5) mm. It is inserted in a cylindrical transmission-type TM_{010} cavity having dimensions according to Figure 25. The ends of the specimen shall pass through holes in the cavity wall; the hole diameter being (1,64 ± 0,01) mm. The input and output lines of this cavity shall be made to appear as matched loads by the appropriate use of pads or isolators. The loaded Q of the cavity shall exceed 2 000. The test specimen shall be in a clean and dry state. There shall be a sufficiently strong axial magnetic field, as otherwise erroneous values of ε'' will be obtained due to the presence of magnetic losses [13].

10.5 Measuring apparatus

Figure 26 is a schematic diagram of the equipment required for the measurement. Power from a suitable unmodulated or amplitude modulated microwave source A is fed through a variable attenuator D and kept at a constant level throughout the measurement with the aid of a directional coupler E, a crystal detector and a power-indicating meter F. This constant power is passed through a precision variable attenuator G to the cavity H, and the cavity output power is detected and indicated on a suitable meter I.

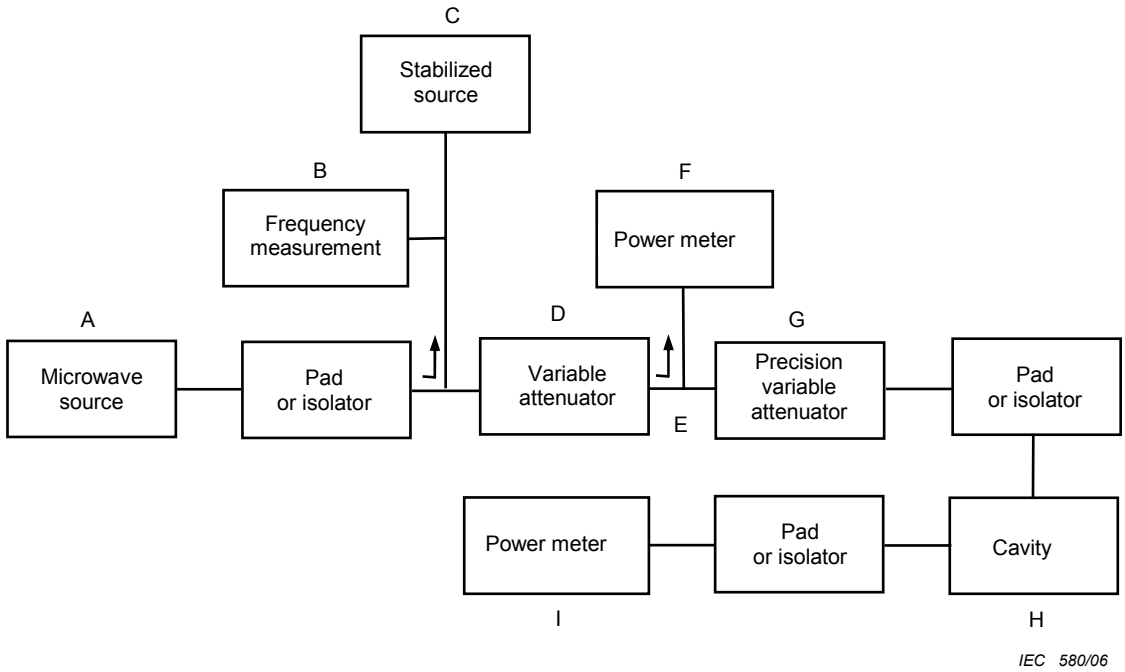


Figure 26 – Schematic diagram of equipment required for the measurement of complex dielectric constant

10.6 Measurement procedure

Introduce an attenuation of 3 dB with the precision attenuator. Without the specimen in the cavity, adjust the microwave frequency to cavity resonance, as indicated by maximum power output with respect to frequency variation. Note the output power level and measure the resonant frequency f_0 with a wavemeter or other suitable means at B. Remove the 3 dB of attenuation and locate the two frequencies at which the output power is the same as at cavity resonance with the 3 dB attenuation in. Determine the separation in frequency of these two half-power points at B by a heterodyning technique utilizing a frequency stabilized source C, or any other technique giving comparable accuracy. The loaded Q of the cavity is then given by

$$Q_0 = \frac{f_0}{\Delta f_{1/2}} \tag{60}$$

where $\Delta f_{1/2}$ is the frequency separation of the half-power points.

Place the specimen in the cavity and measure f_1 and Q_1 in the same way.

During the measurement, the specimen shall be in an axial magnetic field. The field strength shall be high enough for the measuring results to be independent of any further increase (normally above 400 kAm^{-1}). The measurements shall preferably be carried out at room temperature.

10.7 Calculation

The values of ε' and ε'' are calculated by means of equations (58) and (59) and the dielectric loss factor is given by $\tan \delta_\varepsilon = \varepsilon''/\varepsilon'$.

10.8 Accuracy

The error of the approximation for ε' by equation (58) is practically negligible [13].

The approximation for ε'' by equation (59) gives a figure which is too high. The error is less than 3 % if $\delta f / f_0 < 0{,}17$, i.e. if $\varepsilon' < 16$ [13].

The effect of the coupling holes is to increase the measured value of ε''. This error is less than $1{,}5 \times 10^{-4}$ for $\varepsilon' < 16$. For the influence of the magnetic loss, see 10.4 and [13].

An error in the specimen diameter $2b$ (Figure 24) results in a relative error in $(\varepsilon' - 1)$ and ε'' which is twice as high and has reciprocal sign, i.e. $\mp 1{,}3$ % with $b = (1{,}60 \pm 0{,}01)$ mm.

Due to the influence of the holes in the walls of the cavity (into which the ends of the specimen protrude), the measured value of ε' is too small. Differing results have been published on the extent of the error thus introduced [16] [17] [18].

10.9 Data presentation

The report shall include the following:

values of ε', ε'' and tan δ_ε;

temperature of the material during the measurement; and

the unique identity of specimen.

The estimated accuracy of the measurements shall also be given.

11 Apparent density ρ_{app}

11.1 General

The apparent density of a material, defined as the ratio of the mass to the volume of a standard test specimen, may be measured either by mensuration or by water densitometry. For porous materials (where the porosity is greater than 3 %), mensuration yields a sufficient accuracy (± 1 %) and may be more convenient than water densitometry. For materials of low porosity (less than 3 %), a more accurate estimate of apparent density is required and water densitometry is recommended.

11.2 Apparent density (by mensuration)

11.2.1 Object

To measure the apparent density of porous polycrystalline gyromagnetic materials by mensuration. The method is applicable to materials whose porosity is greater than 3 % by volume. It is also admissible for materials whose porosity is less than 3 % by volume, but the alternative method as given in 11.3 below is to be preferred on accuracy and economic considerations.

The method given here is capable of accuracy better than ±1 %.

11.2.2 Test specimen

The test specimen shall be a regular, machined body of volume not less than 5 cm^3. It may be either a straight circular cylinder or a right-angled parallelepiped. If a parallelepiped is employed, it should ideally be a cube since for a given volume of sample machined to a given absolute tolerance the errors due to machining accuracy will then be a minimum. The specimen shall be cleaned by boiling in fresh methylene chloride for 3 min and subsequently dried for 30 min at approximately 110 °C. Other cleaning methods capable of achieving the same result are also acceptable.

11.2.3 Measuring apparatus

A balance capable of weighing to an accuracy of ±0,02 g is required together with a calibrated micrometer reading to ±0,01 mm.

11.2.4 Calibration

The balance shall be calibrated to the accuracy given in 11.2.3 above.

11.2.5 Measuring procedure

The cleaned, degreased and dried specimen is weighed and its dimensions measured. Two independent weighings shall be made and at least two independent estimates of each dimension shall be obtained.

11.2.6 Calculation

The apparent density of the test specimen is calculated as:

$$\rho_{\text{app}} = m / V \tag{61}$$

where

m is the mass of the specimen;

V is the volume as calculated from the linear dimensions.

11.2.7 Accuracy

The method is inherently beset by inaccuracies arising from random macroscopic defects in the specimen shape, particularly chipping along edges and at corners. If the sample is a cube of volume much less than 5 cm^3, this source of error becomes serious and may be greater than ±1 %. Errors due to edge chipping may be minimized by increasing the cube volume, or alternatively by choosing a cylindrical shape of similar volume. In the cylindrical case, the error may further be minimized by choosing the length to be large compared with the diameter. The mensuration method will always underestimate the true apparent density since it assumes that all surface defects are an intrinsic property of the test specimen.

11.2.8 Data presentation

Apparent density shall be quoted as follows:

"Apparent density (by mensuration) = $\rho g \cdot$ cm^{-3} ± 1 %", where the number ρ is given to three significant figures.

The report shall also include the unique identity of the sample.

11.3 Apparent density (by water densitometry)

11.3.1 Object

To measure the apparent density of dense polycrystalline gyromagnetic materials by water densitometry. The method is applicable to non-hygroscopic, dense ceramic materials whose porosity is less than 3 % by volume, and is capable of an accuracy better than ±0,2 %.

11.3.2 Theory

An accuracy of the order of ±0,2 % is required if measurements of apparent density are to have any useful meaning, since real variations of more than 0,5 % of the density frequently imply an intolerable variation in other properties of the material. Since there is no serious difficulty in achieving weighings accurate to the order of ±0,02 %, it is the measurement of volume which becomes the accuracy determining step. Provided that the porosity is sufficiently low for the pores not to be interconnected, the most accurate and economic method of measuring volume, and hence the density, is by displacement of water. In this method, the volume V of the sample is determined from the difference between the mass of the sample suspended in air and its apparent mass when suspended in water.

Thus

$$V = (m_1 - m_2)/(\rho_{\mathrm{w}} - \rho_{\mathrm{a}}) \tag{62}$$

where

m_1 is the mass of the sample suspended in air;

m_2 is the apparent mass of the sample suspended in water;

ρ_{w} is the density of water under the measurement conditions;

ρ_{a} is the density of air under the measurement conditions.

The apparent density is then

$$\rho_{\mathrm{app}} = \frac{m_1\rho_{\mathrm{w}} - m_2\rho_{\mathrm{a}}}{m_1 - m_2} \tag{63}$$

11.3.3 Test specimen

The test specimen shall be a regular, machined body of volume not less than 1 cm^3. The specimen shall be cleaned by boiling in fresh methylene chloride for 3 min, and subsequently dried for 30 min at approximately 110 °C. Other cleaning methods capable of achieving the same result are also acceptable.

11.3.4 Measuring apparatus

The measurement requires a balance capable of weighing to ± 0,001 g and a vessel containing distilled water. The aperture of the vessel shall be not less than three times the maximum dimension of the test specimen.

11.3.5 Calibration

The balance shall be calibrated to the accuracy given in 11.3.4 above.

11.3.6 Measuring procedure

The cleaned and degreased test specimen is weighed in air (m_1). The specimen is then weighed (m_2) completely immersed in distilled water, care having been taken to ensure that all surfaces of the specimen are thoroughly wetted and that no air bubbles adhere. A small quantity of wetting agent may be added to the water if desired, and the temperature of the water shall be noted.

11.3.7 Calculation

The apparent density of the test specimen is calculated from equation (63), the values of ρ_w and ρ_a being obtained from standard tables [19].

11.3.8 Accuracy

Sources of random error include:

a) the failure of the water to wet the specimen surface thoroughly and the consequent adherence of air bubbles thereto: this leads to a random tendency to underestimate the density;

b) inaccuracies in the weighings themselves. Reasonable precautions as outlined above will result in the sum of random errors being no greater than ±0,1 %.

The most significant sources of systematic error are:

1) the presence of surface porosity in the test specimen, and

2) incorrect values for ρ_w and ρ_a, the densities of water and air respectively.

   Failure to allow for ρ_a results in a systematic error of order 0,1 % and failure to allow for deviations of ρ_w from unity as the water temperature differs from 4,0 °C results in a systematic error of about 0,02 % per degree Celsius. Provided that the porosity is less than 3 %, the error due to exposed surface pores may be neglected; beyond about 3 % porosity, the errors due to interconnection become significant and the method is no longer appropriate. For dense materials, as defined in 11.3.1, this method is advantageous over mensuration since the errors due to macroscopic surface irregularities are entirely avoided. The method, as described, is capable of an accuracy of typically ±0,2 %, as compared with ±1 % by mensuration of a similar size specimen.

11.3.9 Data presentation

The apparent density shall be quoted as follows:

"Apparent density (by mensuration) = $\rho g \cdot \mathrm{cm}^{-3}$ ± 0,2 %", where the number ρ is given to three significant figures.

The report shall also include the unique identity of the sample.

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