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AMENDMENT 1
AMENDEMENT 1

Gyromagnetic materials intended for application at microwave frequencies – Measuring methods for properties

Matériaux gyromagnétiques destinés à des applications hyperfréquences – Méthodes de mesure des propriétés

IEC 60556:2006-04/AMD1:2016-03(en-fr)

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FOREWORD

This amendment has been prepared by IEC technical committee 51: Magnetic components and ferrite materials.

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

CDV	Report on voting
51/1064/CDV	51/1089A/RVC

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

The committee has decided that the contents of this amendment and the base publication will remain unchanged until the stability date indicated on the IEC website 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- withdrawn,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.

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Add, after Clause 11, the following new Clause 12 and Annex A:

12 Gyromagnetic resonance linewidth ΔH and effective gyromagnetic ratio γ_{eff} by non resonant method

12.1 General

So far the gyromagnetic resonance linewidth ΔH and the effective gyromagnetic ratio γ_{eff} have been measured by using the resonant cavity as described in Clause 6. Therefore, the measuring frequency is restricted to the frequency specified by a cavity resonator.

Meanwhile, various kinds of ferrite devices have been developed in a wide frequency range.

Accordingly it is desirable to measure the gyromagnetic resonance linewidth ΔH and the effective gyromagnetic ratio γ_{eff} easily at any frequency demanded for the development of ferrite materials or devices. Moreover, there are two problems in the cavity resonator method described in Clause 6. One problem is the insufficient resolution of a magneto flux density meter, which is apt to cause poor accuracy in the measurement of the narrow resonance linewidth. Another problem is that a ferrite sample becomes too small to be shaped into a sphere or a disk, because it is necessary to reduce the size of a ferrite sample to keep the resonance absorption increasing with the reduction of the resonance linewidth to proper values in order to ensure a sufficiently small cavity perturbation. In Clause 12, the measuring methods of the gyromagnetic resonance linewidth ΔH and the effective gyromagnetic ratio γ_{eff} at an arbitrary frequency are described.

12.2 Object

To describe methods that can be used for measuring the gyromagnetic resonance linewidth ΔH and the effective gyromagnetic ratio γ_{eff} of isotropic microwave ferrites at an arbitrary frequency over the frequency range of 1 GHz to 10 GHz by the measurement of the changes in transmission and reflection characteristics with frequency sweep.

12.3 Measuring methods

12.3.1 General

The measurements are performed by measuring the changes of transmission characteristics, such as complex reflection coefficients or scalar transmission coefficients, in a transmission line loaded with a ferrite sample with frequency sweep. The advent of a frequency synthesizer and a receiver with low noise figure and a wide dynamic range in the microwave region has made it possible to perform these measurements accurately.

Strictly speaking, the linewidth measured under frequency sweep and a constant external magnetic field is not the same as the one measured under external magnetic field sweep and a constant frequency as described in Clause 6. However the difference between two measured values is small to the extent that it causes no problem in practical use.

As the measuring method, two methods can be considered as follows:

1) Reflection method – method measuring the reflection coefficients from the short-circuited transmission line loaded with a ferrite sample.
2) Transmission method – method measuring the transmission power through a ferrite-loaded coupling hole made in a common ground plane of the transmission lines crossing at right angle.

These two methods have advantages and disadvantages in comparison with each other from the standpoint of practical use. The reflection method has the advantage of a simple test fixture’s structure, easier sample mounting and simpler measuring circuit arrangement due to one port measurement, which is convenient for the measurement of temperature dependence of the resonance linewidth. The transmission method has the advantage of being able to measure the resonance linewidth by one ferrite sample in a wide frequency range and gives more accurate measuring values of the resonance linewidth due to simpler measurement, i.e. the measurement of the transmission power only, under careful making of a test fixture.

These two methods are enumerated in 12.3.2 and 12.3.3.

12.3.2 Reflection method

12.3.2.1 Measurement theory

The recommended method for measuring the gyromagnetic resonance linewidth ΔH and effective gyromagnetic ratio γ_{eff} is based on the measurement of the reflection coefficient S_{11} of a short-circuited transmission line with the specimen as proposed by Bady [20]. In this standard, the short-circuited microstrip line is used as schematically shown in Figure 27.

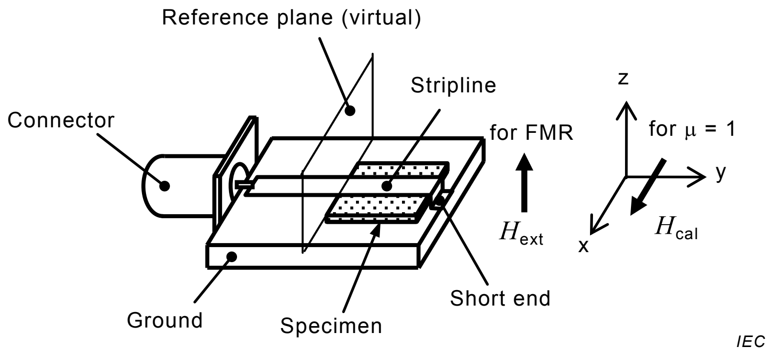


Figure 27 – Schematic drawing of short-circuited microstrip line fixture with specimen

The reference plane is defined by the length of the specimen from the short end. Seen from the reference plane of the test fixture, the lumped element equivalent circuit can be assumed to be a $L_o C_o$ parallel circuit as in Figure 28a) when the strong magnetic field is applied parallel to the plane of specimen (x-direction) to achieve the situation of $\mu = 1$. After removing this field, the field is applied perpendicularly to the specimen plane for gyromagnetic resonance. Figure 28b) shows the equivalent circuit for gyromagnetic resonance [21], where L_o is an air core inductance and C_o is a parasitic capacitance. The values of L_o and C_o are designated “fixture constants”. The method to calculate “fixture constants” is shown in 12.3.2.8. When a gyromagnetic resonance occurs, it is considered that some portion η of air core inductance L_o is replaced by the complex relative permeability μ' μ'', and the coupling coefficient η is almost invariable within the measurement frequency range. The half value width of the resonant curve of the imaginary part μ'' is defined as gyromagnetic resonance linewidth. By measuring the S_{11} parameters of Figure 28a) and 28b), the quantity $\eta\mu'' L_o$ proportional to the imaginary part μ'' can be derived based on the circuit theory analysis as shown in 12.3.2.5.

Consequently the gyromagnetic resonance linewidth ΔH is derived from the resonance curve of $\eta\mu'' L_o$.

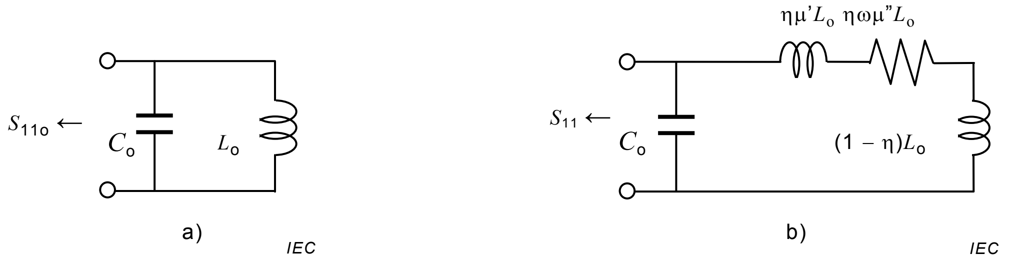


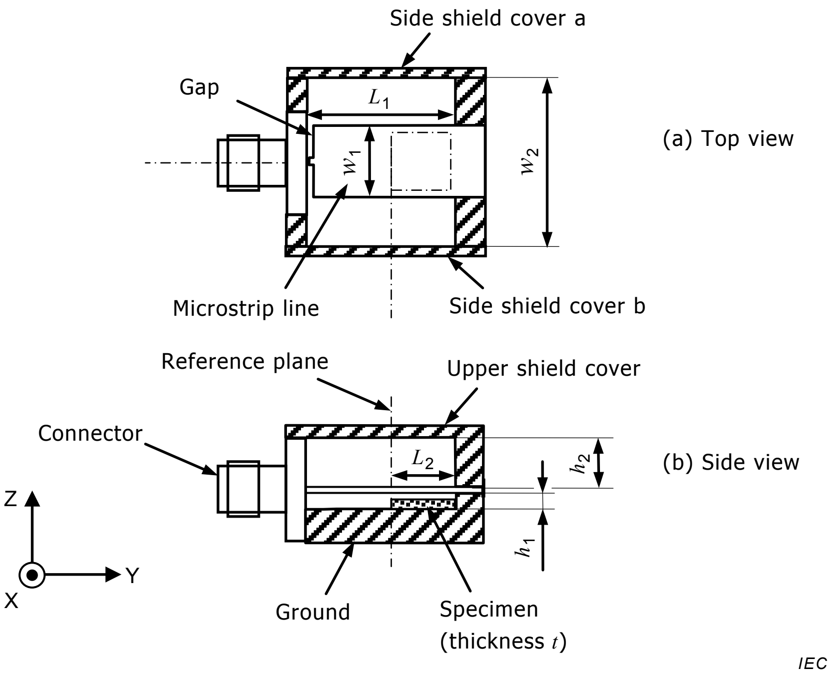
Figure 28a) with μ = 1 under strong magnetic field parallel to r.f. magnetic field

Figure 28b) with gyromagnetic resonance

Figure 28 – Equivalent circuits of short-circuited microstrip line

12.3.2.2 Test specimens and test fixtures

The structure of the all-shielded short-circuited microstrip line as test fixture is shown schematically in Figure 29. A disk shape or square slab specimen is set at the end of the short-circuited portion. To avoid disturbance from outside, the shielded covers are set up on the upper side and both sides of the test fixture. The impedance of the test fixture except the short end should be made at 50 Ω ± 2 Ω by adjusting the gap between the connector and the strip line. The typical dimensions of the test fixture are shown in Table 1.



NOTE The thickness of the strip line is 0,3 mm.

Figure 29 – Cross-sectional drawing of all-shielded shorted microstrip line with specimen

Table 1 – Typical dimensions of test fixture

h_1	w_1	h_2	gap	w_2	L_1	L_2
2,0	7,0	3,7	0,35 ± 0,15	20	8	5
NOTE Dimensions in mm.						

The shapes of specimens are a disk or a square slab. The typical dimensions of specimens are shown in Table 2.

Table 2 – Specimen shape and typical dimensions

Disk	Diameter D $D \leq 5$ mm ϕ up to 10 GHz	Quotient of diameter and thickness $t/D \leq 1/20$ (t = thickness)
Square slab	Side length $L_2 \leq 5$ mm up to 10 GHz	Quotient of side length and thickness $t/L_2 \leq 1/20$ (t = thickness)

12.3.2.3 Measuring apparatus

Figure 30 shows the block diagram of this measurement method. The test fixture with a specimen is located between pole pieces of permanent magnets or an electro magnet to generate gyromagnetic resonance. In case of a disk or square slab, in order to apply a static magnetic field in normal to plane, the test fixture and pole piece should be capable of rotating along two different axes which are orthogonal to each other. Under the constant static magnetic field, the absolute value and phase of the S_{11} parameter of the test fixture are measured by the sweeping frequency of the vector network analyzer (VNA).

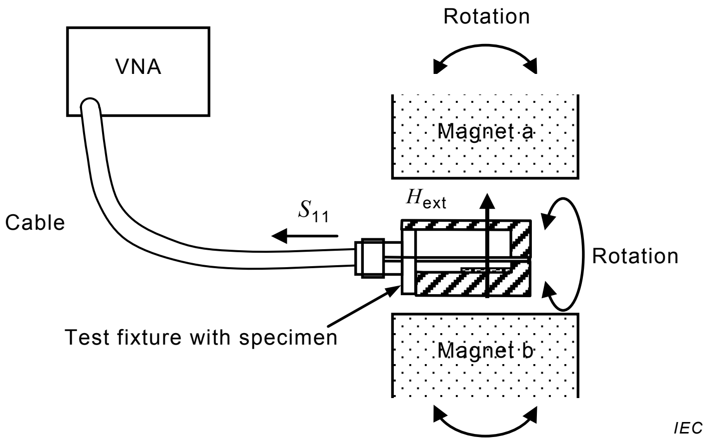


Figure 30 – Block diagram of measurement system

12.3.2.4 Measuring procedure

The measuring procedure is as follows:

1) The VNA is calibrated on the cable end using an “open”, “short”, and “load” jig.
2) The total sweeping frequency points are selected so as to get more than 10 points within the half linewidth Δf of the frequency defined below.
3) A specimen should be contacted and fixed on the corner of the short end and the ground.
4) To sustain the situation of $\mu = 1$, a static magnetic field H_{cal} larger than $3,2 \times 10^5$ A/m should be applied in parallel to the x-direction of the r. f. magnetic field.
5) The absolute value and phase of S_{11o} are measured as shown in Equation (64).

$$S_{11o} = G_o \exp(j\delta_o) \tag{64}$$

6) After removing H_{cal}, the static magnetic field H_{ext} is applied along the z-direction.
7) The gyromagnetic resonance curve is observed in S_{11}.
8) The direction of H_{ext} is adjusted to obtain the lowest resonant frequency, namely to be normal to the plane of the specimens, by rotating the test fixture and pole pieces individually.
9) The minimum value S_{11m} is measured at the resonant frequency. This value should be less than –1 dB.
10) Then the absolute value and phase of S_{11} are measured all over the frequency range as shown in Equation (65).

$$S_{11} = G \exp(j\delta) \tag{65}$$

12.3.2.5 Derivation of gyromagnetic resonance linewidth ΔH [21]

The derivation of gyromagnetic resonance linewidth is obtained as follows:

1) By dividing Equation (65) by Equation (64), E and F are defined as Equation (66).

$$S_{11}/S_{11o} = G/G_o \exp\{j(\delta - \delta_o)\} = E + j F \tag{66}$$

2) Next, the calculations should be done.

$$C_{11} = y(E + 1) + F X_c \tag{67}$$

$$C_{12} = X_c (E-1) - y F \tag{68}$$

$$C_{10} = y \{ y (1-E) - F X_c \} \tag{69}$$

$$C_{20} = y \{ X_c (1+E) - F y \} \tag{70}$$

where

y is a characteristic admittance, usually y = 0,02 S.

X_c is defined by $X_c = \omega C_o - 1/\omega L_o$ (71)

3) Also, the following calculations should be done.

$$A = \frac{C_{10}C_{11} - C_{20}C_{12}}{C_{11}^2 + C_{12}^2} \tag{72}$$

$$B = \frac{C_{10}C_{12} + C_{20}C_{11}}{C_{11}^2 + C_{12}^2} \tag{73}$$

4) The imaginary part $\eta\mu'' L_o$ of the complex inductance is calculated.

$$\eta\mu'' L_o = \frac{A}{\varpi \{ A^2 + (B - \varpi C_o)^2 \}} \tag{74}$$

5) The value of $\eta\mu'' L_o$ is directly proportional to μ''. With $\eta\mu'' L_o$ being on the vertical axis and the frequency being on the horizontal axis, the resonance curve can be drawn as shown in Figure 31. In general, the curve is not always bilaterally symmetrical on the central frequency axis. The resonant frequency f_r of the main peak and two half line widths of Δf_l on the left and Δf_h on the right could be derived. However, the smaller value of Δf_l on the left side than of Δf_h on the right side is adopted as a correct half width Δf because the smaller one is considered to be less influenced by a higher magneto static mode. The method to derive Δf using the least square method is shown in 12.3.2.6.

6) The relaxation constant α is derived by the Equation (75) [22].

$$\alpha = \Delta f / f_r \tag{75}$$

7) The gyromagnetic resonance linewidth ΔH is derived through Equation (76) [23].

$$\Delta H = 4\pi \Delta f / (\mu_o \gamma_{eff}) \text{ (A/m)} \tag{76}$$

where

μ_o is the permeability of vacuum;

γ_{eff} is the effective gyromagnetic ratio.

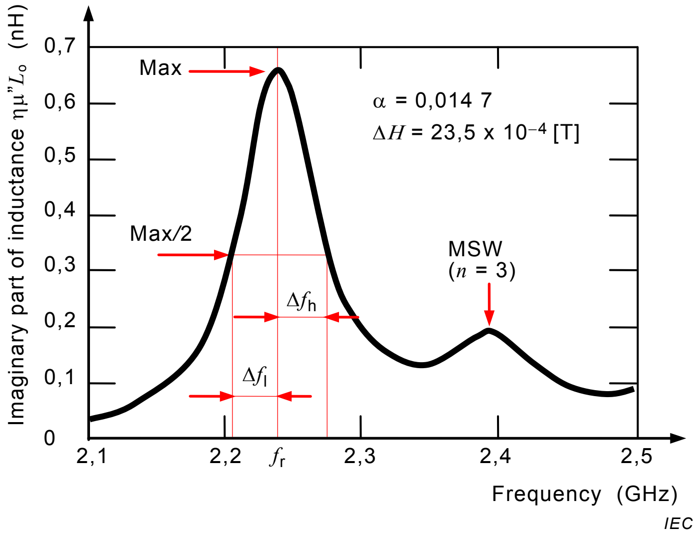


Figure 31 – Observed absorption curve of imaginary part ημ"L_o of inductance for a 5 mm square garnet specimen with 0,232 mm thickness and Ms = 0,08 T

NOTE If the amplitude and phase of S_{11} are measured with an accuracy of ±0,02 dB and ±0,075° respectively, the static magnetic field strength is measured with an accuracy of ±1 %, and L_o and C_o are determined with an accuracy ±10 %, the relative error of γ_{eff} becomes equal to ±1 % and the relative error in the determination of ΔH becomes equal to ±5 %, respectively.

12.3.2.6 The derivation of half line width Δf by the least square method

First, as an example, the measurement values ημ"L_o of about 10 pieces on the lower frequency side and of about 4 pieces on the higher frequency side including the maximum value of (ημ"L_o)$_{max}$ are gathered. Next, the inverse value of (ημ"L_o)$_{max}$ is denoted as $a(0)$ and the inverse values of ημ"$L_o(i)$ on both sides are denoted as $a(-10)$, $a(-9)$, ... $a(-1)$, $a(1)$, $a(2)$, and $a(3)$. The corresponding frequencies are $f(0)$, $f(-10)$, $f(-9)$, ... $f(-1)$, $f(1)$, $f(2)$, and $f(3)$ respectively, where the lowest frequency is $f(-10)$. Then the new frequency sets of $F(i) = f(i) - f(-10)$ are introduced. The value of $a(i)$ obeys the parabolic relation as in Equation (77) because ημ"$L_o(i)$ has Lorentzian characteristics.

$$y(i) = P\,F(i)^2 + Q\,F(i) + R \qquad (77)$$

where P, Q, and R are the coefficients which should be determined by the least square method. The error function of E^2 is defined as follows:

$$E^2 = \Sigma\{y(i) - a(i)\}^2 = \Sigma\{P\,F(i)^2 + Q\,F(i) + R - a(i)\}^2 \quad (i = -10, -9, \ldots 0, 1, 2, 3) \qquad (78)$$

The partial differentiations are performed regarding P, Q, and R to minimize E^2.

Eventually, the coefficients of P, Q, and R could be determined by the next equations.

$$P = D_P / D,\ Q = D_Q / D,\ R = D_R / D \qquad (79)$$

where

$$D = \begin{vmatrix} X_4 & X_3 & X_2 \\ X_3 & X_2 & X_1 \\ X_2 & X_1 & n \end{vmatrix} \quad Dp = \begin{vmatrix} X_2A & X_3 & X_2 \\ X_1A & X_2 & X_1 \\ A & X_1 & n \end{vmatrix} \quad D_Q = \begin{vmatrix} X_4 & X_2A & X_2 \\ X_3 & X_1A & X_1 \\ X_2 & A & n \end{vmatrix} \quad D_R = \begin{vmatrix} X_4 & X_3 & X_2A \\ X_3 & X_2 & X_1A \\ X_2 & X_1 & A \end{vmatrix} \qquad (80)$$

where

$$X_4 = \Sigma\, F(i)^4 \;,\; X_3 = \Sigma\, F(i)^3 \;,\; X_2 = \Sigma\, F(i)^2 \;,\; X_1 = \Sigma\, F(i) \;,\; n = \Sigma\, F(i)^0 \tag{81}$$

$$X_2\, A = \Sigma\, F(i)^2\, a(i),\; X_1\, A = \Sigma\, F(i)\, a(i),\; A = \Sigma\, a(i) \tag{82}$$

where n is the total number of the data. In this example $n = 14$.

As a result, the resonance frequency f_r is given by the Equation (83).

$$f_r = -Q\,/(2\,P) + f(-10) \tag{83}$$

The half line width Δf is also given by the Equation (84).

$$\Delta f = \frac{\sqrt{4PR - Q^2}}{P} \tag{84}$$

12.3.2.7 Calculation of effective gyromagnetic ratio γ_{eff}

The value of γ_{eff} could be derived through the next procedure.

1) By changing an applied magnetic field from H_1 to H_2, the resonant frequency f_{r1} and f_{r2} can be measured correspondingly.
2) The effective gyromagnetic ratio γ_{eff} is derived by Equation (85).

$$\gamma_{eff} = \frac{2\pi(f_{r1} - f_{r2})}{\mu_o(H1 - H2)}\left(T^{-1}s^{-1}\right) \tag{85}$$

where

the frequency difference $(f_{r1} - f_{r2})$ should be larger than 600 MHz.

12.3.2.8 Calculations of fixture constant L_o and C_o

The equivalent circuit seeing a specimen with $\mu = 1$ from the reference plane is assumed to be a parallel circuit with L_o and C_o as shown in Figure 32.

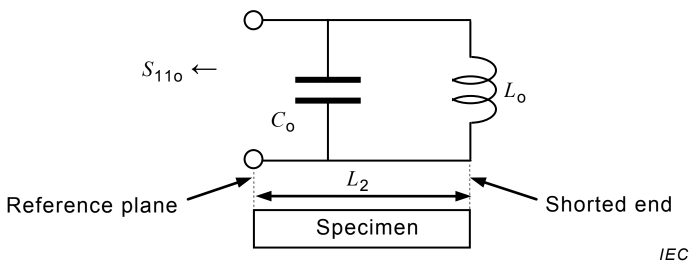


Figure 32 – Assumed equivalent circuit of the test fixture

If the test fixture impedance is designed to be 50 Ω except the short end and the effect of the loading sample with $\mu = 1$ is negligible, the fixture constants of L_o and C_o are calculated as follows:

$$L_o = L\, L_2\ (H) \tag{86}$$

$$C_o = 0{,}38\ C\ L_2\ (F) \qquad (87)$$

where

L_2 is the length of the sample, and L = 166,9 nH/m and C = 66,67 pF/m [24] are the inductance and the capacitance per unit length of the 50 Ω transmission line. The factor of 0,38 in Equation (87) was determined to minimize the lumped element model error in the wide measurement frequency range up to 10 GHz.

Table 3 shows the calculated fixture constants for 5 mm long specimens.

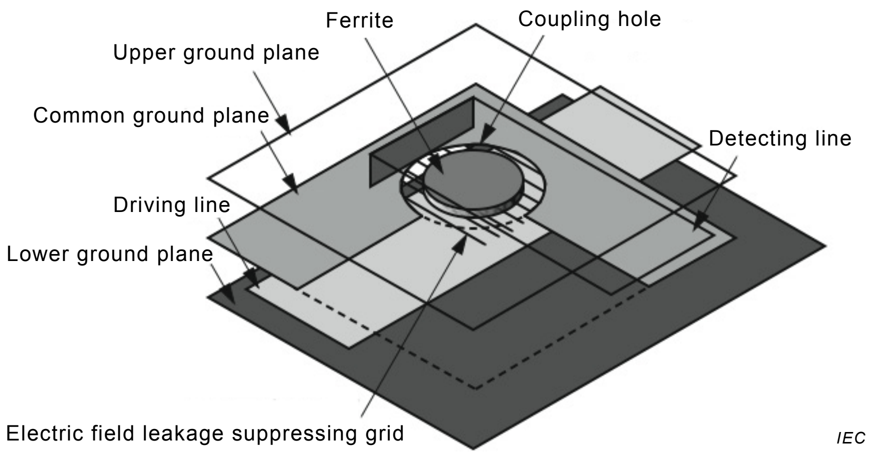
Table 3 – The fixture constants for 5 mm long specimens

Length of specimen mm	L_o nH	C_o pF
5	0,834	0,127

12.3.3 Transmission method

12.3.3.1 Theory

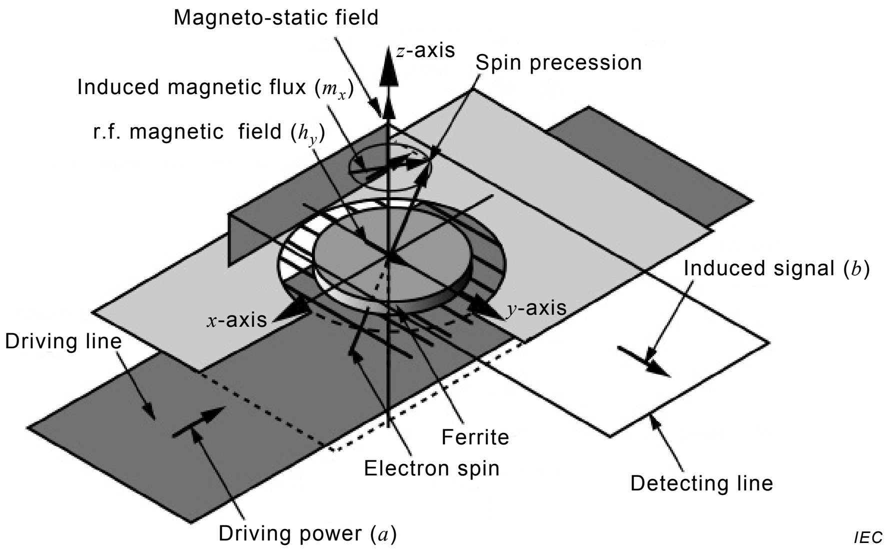
A method recommended for the evaluation of ΔH and γ_{eff} at an arbitrary frequency is based on the measurement of the off-diagonal element of relative tensor permeability, κ, through a signal transmission [25]. A test fixture model used in this measurement is shown in Figure 33. The test fixture is constructed by two tri-plate lines stacked at right angle and a common ground plane between them with a coupling hole at the cross point of the two lines. One line used to apply an r.f. magnetic field to a specimen is terminated by a matched load to generate a uniform r. f. magnetic field. The other line used to detect a signal from the specimen is grounded at the edge of the coupling hole to avoid an error caused by leakage of an electric field from the coupling hole. A grid parallel to the driving r. f. magnetic field is provided in the coupling hole for further suppression of the electric field leakage.



(A part of the ground plane is cut away to show the bottom part of the test fixture.)

Figure 33 – Structure of test fixture to measure resonance linewidth by transmission

A ferrite specimen is positioned on the electric field leakage suppressor grid, facing the detecting line. A magneto-static field orthogonal to the driving r. f. magnetic field is applied to generate a precession of the electron spin in the ferrite and a gyromagnetic resonance. The spin precession induces a signal in the detecting line. These relationships are shown in Figure 34.



(A part of the ground plane is cut away to show the bottom part of test the fixture.)

Figure 34 – Model to measure resonance linewidth by transmission

Through the precession of the electron spin, the application of the magneto-static field to the test fixture results in a coupling between the driving and the detecting lines as shown in Equation (88) [25].

$$C = C_0 + 20\log(|\kappa|) \tag{88}$$

where

C_0 is the coupling coefficient in dB defined by the diameter-wavelength ratio of the hole;

κ is the off-diagonal element of relative tensor permeability of the ferrite specimen in the coupling hole.

Equation (88) shows that the signal intensity obtained from the test fixture is proportional to the absolute value of the off-diagonal element in the relative tensor permeability, κ, of the magnetized ferrite. The resonance is defined by the magneto-static field strength and the frequency to maximize the transmitted power, and the relationship between the resonance frequency and the internal magnetic field of the specimen is written as shown in Equation (89).

$$f_r = \frac{\gamma_{eff} H_i}{2\pi} \tag{89}$$

where

f_r is the resonance frequency;

γ_{eff} is the effective gyromagnetic ratio;

H_i is the internal magnetic field of the specimen.

The linewidth in the frequency, Δf, is defined as the difference between the two frequencies f_1 and f_2 at which the transmitted power by the ferrite material is one-half the maximum transmission as shown below.

$$\Delta f = |f_1 - f_2| \tag{90}$$

The line broadening by the external load is included in the linewidth. The broadening is adjusted from the maximum value of the transmission as described in 12.3.3.5. The linewidth