Hewlett-Packard

Electronic Materials Measurement Seminar

Permeability (Magnetic) Measurements

Kobe Instrument Division

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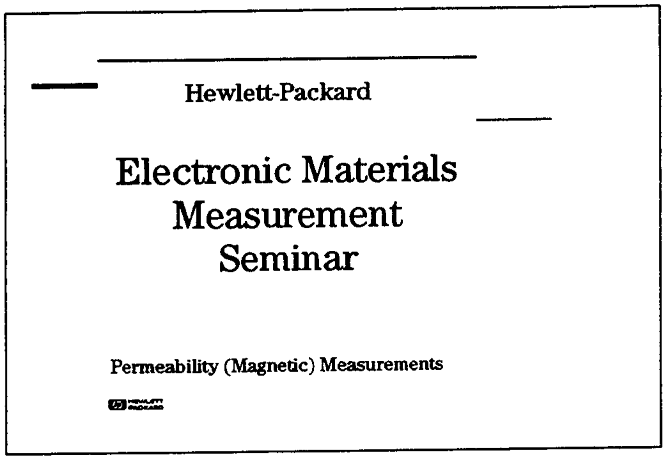

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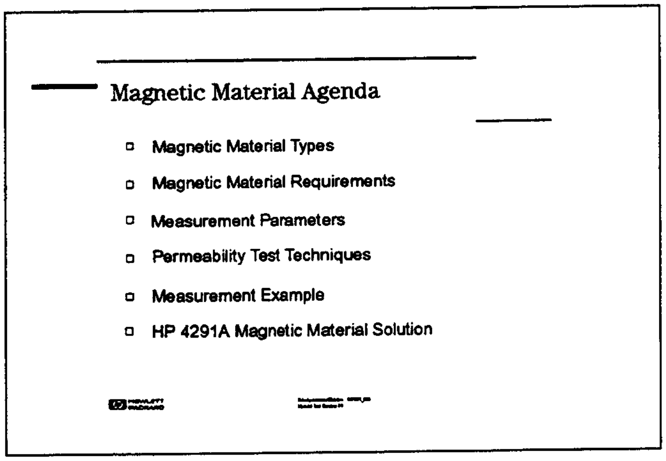

Magnetic Material Agenda

- Magnetic Material Types
- Magnetic Material Requirements
- Measurement Parameters
- Permeability Test Techniques
- Measurement Example
- HP 4291A Magnetic Material Solution

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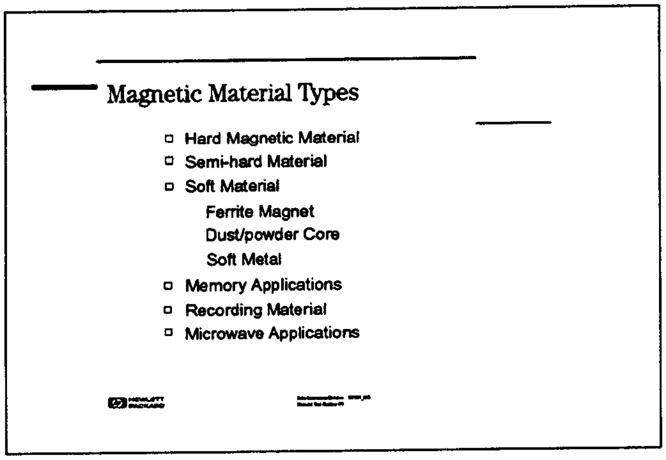

Magnetic Material Types

- Hard Magnetic Material
- Semi-hard Material
- Soft Material
  - Ferrite Magnet
  - Dust/powder Core
  - Soft Metal
- Memory Applications
- Recording Material
- Microwave Applications

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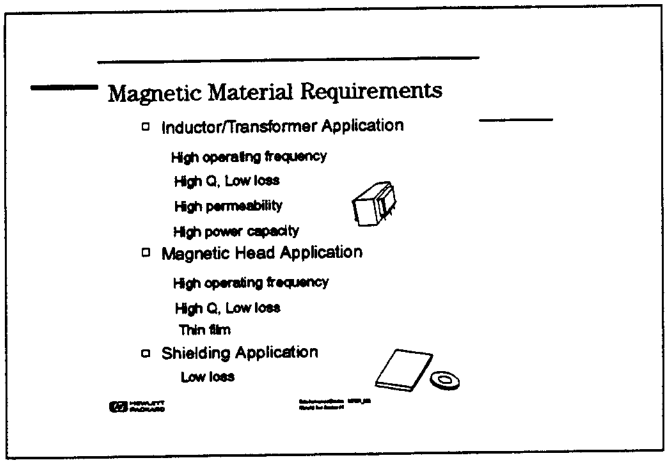
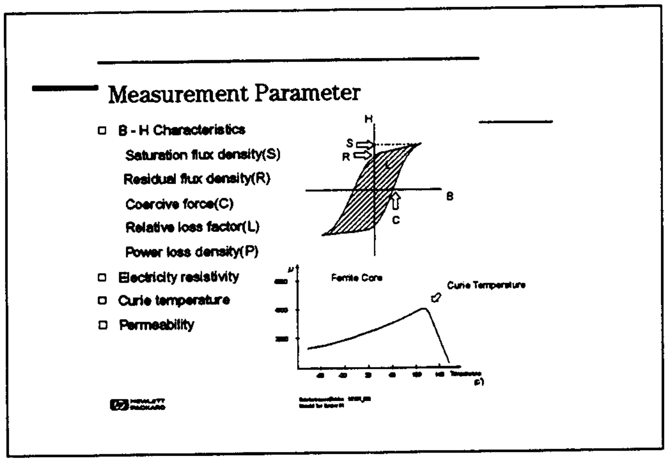
Magnetic material is the generic term for materials whose magnetic characteristics are used for electrical applications. Hard magnetic materials (Al-Ni-Co, Fe-Cr-Co, Mn- Al-C) are used for applications like permanent magnets. Semi-hard magnetic materials (Nb-Fe-Co, Ni-Cu-Fe) are used in the core of relays. Soft magnetic materials have high permeability and high saturation flux densities. They are used in the cores of motors, magnetic heads, transformers, and shielding material. Magnetic material for memory applications are represented by thin film magnetic memory and ferrite core memory. Magnetic recording media (tape, disc, dram) are made of magnetic recording material. RF/uW absorptive materials are magnetic materials used for microwave applications.



Magnetic Material Requirements

- ☐ Inductor/Transformer Application
  - High operating frequency
  - High Q, Low loss
  - High permeability
  - High power capacity
- ☐ Magnetic Head Application
  - High operating frequency
  - High Q, Low loss
  - Thin film
- ☐ Shielding Application
  - Low loss

Here are the typical requirements in testing magnetic materials for major applications. Since the operating frequencies of electrical equipment and components is generally going higher, high frequencies are required for magnetic materials. In magnetic head applications, high frequencies are necessary to reach high densities for magnetic recording. By using low loss shielding material, low transmission impedance material can be developed that have high shielding characteristics.



Measurement Parameter

- ☐ B - H Characteristics
  - Saturation flux density(S)
  - Residual flux density(R)
  - Coercive force(C)
  - Relative loss factor(L)
  - Power loss density(P)
- ☐ Electricity resistivity
- ☐ Curie temperature
- ☐ Permeability

There are several measurement parameters that are used to evaluate magnetic materials. Hysteresis curves (B-H characteristics) yield some parameters for material evaluation. Oscillators and digitizing oscilloscopes can measure the B-H characteristics. The relative loss factor is derived from the area of the hysteresis curve. The power loss density is calculated from relative loss factor and the cross sectional area of the core. Permeability is another important parameter used to evaluate materials. Impedance analyzers and network analyzers can measure the permeability.

Permeability

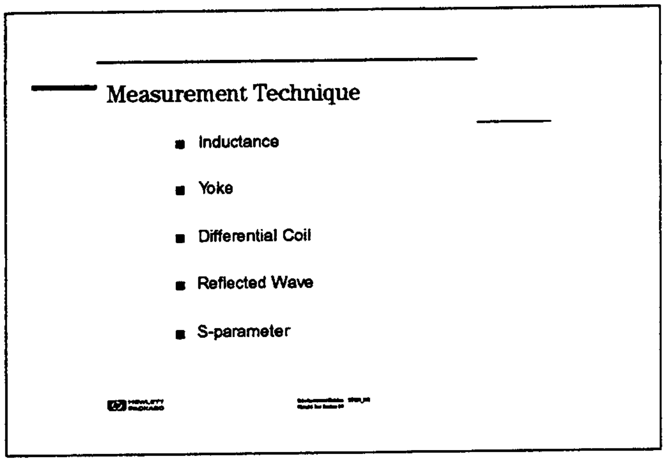
Interaction of a material with a magnetic field

$$\mu_r^* = \frac{\mu^*}{\mu_o} = \underset{\text{(storage)}}{\mu_r'} - j \underset{\text{(loss)}}{\mu_r''} = \left(\frac{\mu'}{\mu_o}\right) - j\left(\frac{\mu''}{\mu_o}\right)$$

μ_r'' = relative permeability

μ_o = permeability of free space = $4\pi \times 10^{-7}$ Henry/meter

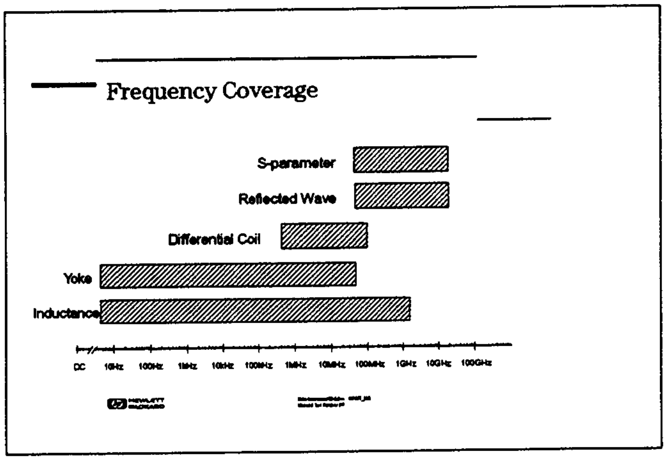
The complex permeability (μ^*) consists of a real part(μ') that represents the energy storage. The imaginary part (μ'') represents the energy loss term. Relative permeability (μ_r) is the absolute permeability (μ) relative to the permeability of free space(μ_0). Some materials such as iron (ferrites), cobalt, nickel and their alloys have appreciable magnetic properties; however, many materials are non-magnetic (paramagnetic) in nature. All materials, on the other hand, have dielectric properties.



Measurement Technique

- Inductance
- Yoke
- Differential Coil
- Reflected Wave
- S-parameter

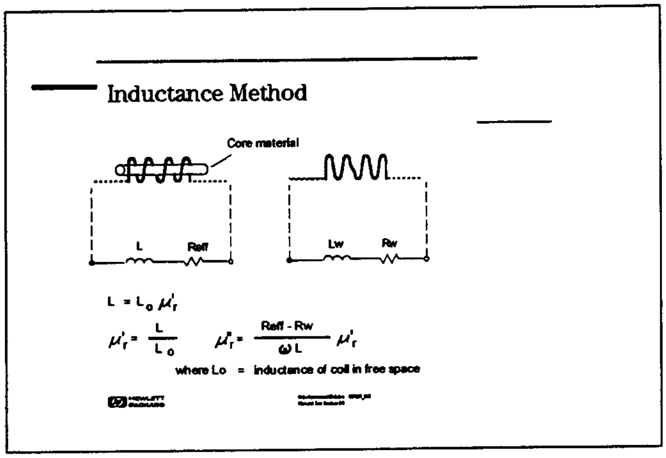
Here are some techniques for measuring permeability. You will have to understand the advantages and disadvantages of these measurement techniques in order to select the best way to evaluate your material.



Frequency Coverage

This figure shows the frequency coverage of each measurement method. The inductance and yoke method have wide a frequency coverage, but they can not be used at high frequencies. The reflected wave and s-parameter method is used to test at high frequencies.

We will discuss about the Inductance measurement method. An Addendum at the end of this presentation has infromation on other measurement methods for permeability.



Inductance Method

$L = L_o \mu'_r$

$\mu'_r = \frac{L}{L_o}$ $\mu''_r = \frac{Reff - Rw}{\omega L} \mu'_r$

where Lo = inductance of coil in free space

The inductance method is derived from the permeability of the self-inductance and resistance of magnetic materials. First, the inductance value (L_o) is measured without the material. Then, the material is put into the inductor and measured for the inductance value (L). Relative permeability is calculated from L/L_o. This method can measure the permeability of cylindric and toroidal materials easily. But it cannot measure thin film materials. Another major disadvantage of this method is that it is frequency limited. Because of the self-resonance caused by distributed capacitance, measurements at high frequencies are difficult.

Inductance Method

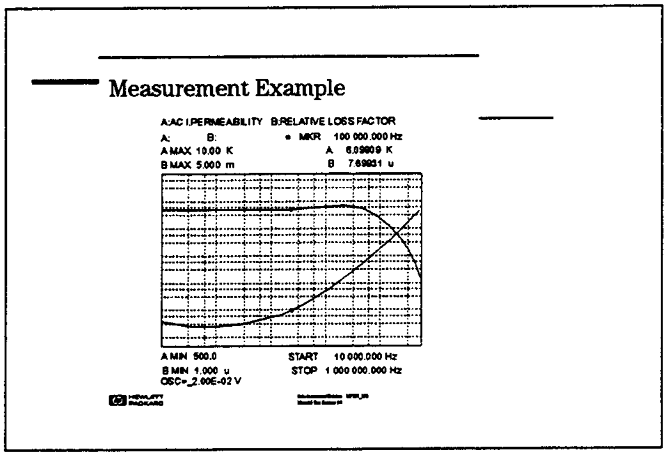
Advantages

- Broad frequency range in low frequencies
- Relatively accurate measurement
- Math is straightforward
- Easy setup with low cost solution

Disadvantages

- High frequency measurement limited by interwinding capacitance
- Can measure only bulk

Since we can use a LCR meter or impedance analyzer to measure the inductance, a wide range of inductance and permeability measurements are possible with a relatively high accuracy (0.1-2%).

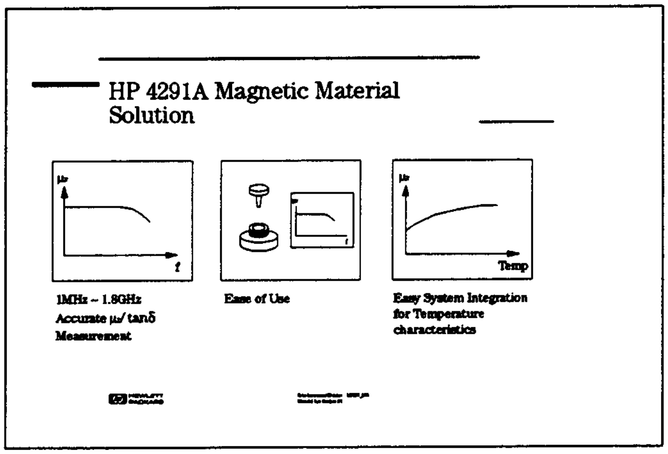


Measurement Example

A:AC I.PERMEABILITY B:RELATIVE LOSS FACTOR
A: B: • MKR 100 000.000 Hz
A MAX 10.00 K A 6.09909 K
B MAX 5.000 m B 7.69931 u

A MIN 500.0 START 10 000.000 Hz
B MIN 1.000 u STOP 1 000 000.000 Hz
OSC=_2.00E-02 V

This is a measurement example of initial AC permeability and relative loss coefficient frequency characteristics. Using the auto sequence program (installed in HP4194A, HP4195A) function, it is possible to automatically calculate, display on the CRT and output the test data to a printer the magnetic material frequency characteristics based on an impedance measurement data. Refer to the application note 339 for details.



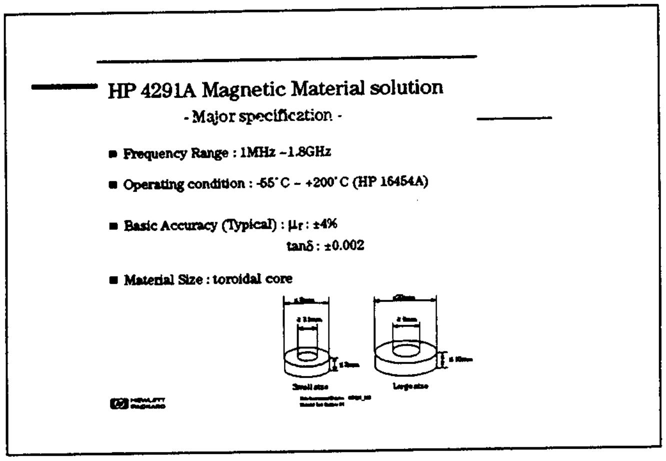
HP 4291A Magnetic Material Solution

1MHz ~ 1.8GHz
Accurate μr/ tanδ
Measurement

Ease of Use

Easy System Integration
for Temperature
characteristics

The HP 4291A material solution is the complete total solution to solve the current problems by offering the accurate μr/tan D versatile analysis with easy operation and easy system integrations.



HP 4291A Magnetic Material solution

- Major specification -

- Frequency Range : 1MHz ~1.8GHz
- Operating condition : -55°C ~ +200°C (HP 16454A)
- Basic Accuracy (Typical) : μ_r : ±4%
  tanδ : ±0.002
- Material Size : toroidal core

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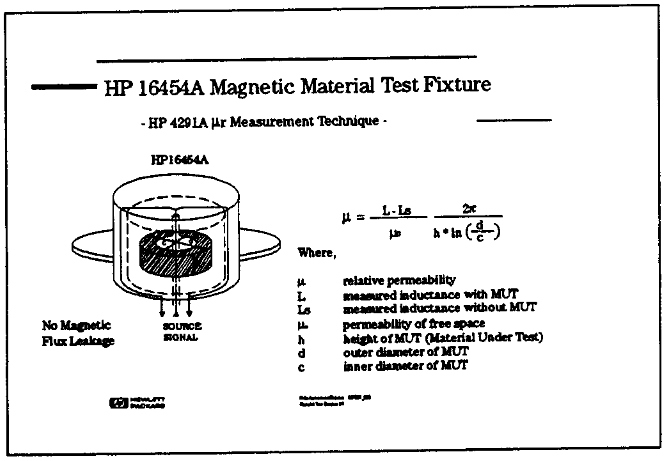
The HP 4291A measures the accurate relative permeability and loss tangent up to 1.8 GHz with the operating condition from -55 degree C to 200 degree C. The HP 16454A comes with two adaptors to accomodate many different sizes of toroidal shaped material.



HP 16454A Magnetic Material Test Fixture

- HP 4291A μr Measurement Technique -

$$\mu = \frac{L - Ls}{\mu_o} \, \frac{2\pi}{h \cdot \ln\left(\frac{d}{c}\right)}$$

Where,

μ relative permeability
L measured inductance with MUT
Ls measured inductance without MUT
μ_o permeability of free space
h height of MUT (Material Under Test)
d outer diameter of MUT
c inner diameter of MUT

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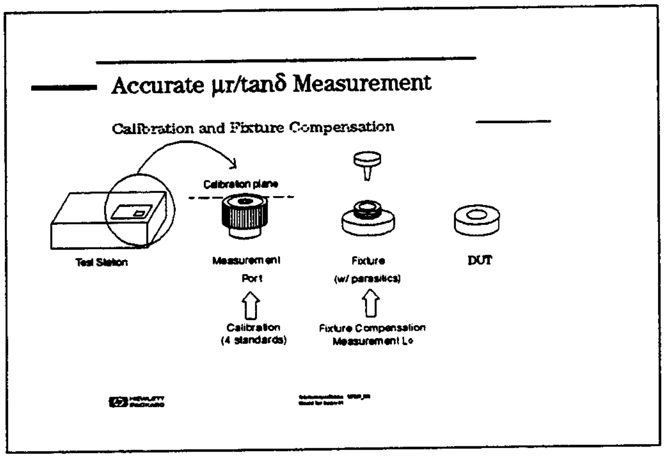
The new HP 16454A test fixture is designed to be ideal structure (no magnetic flux leakage). The relative permeability is derived from the inductance with/without MUT (basically inductor method).



Accurate μr/tanδ Measurement

Calibration and Fixture Compensation

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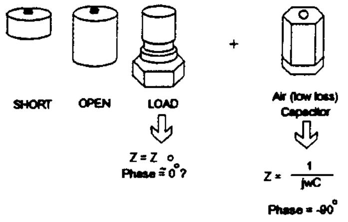
SOLA Calibration for Q/tanδ Accuracy



$Z = Z_0$
$\text{Phase} \doteqdot 0^\circ$?

$Z = \frac{1}{j\omega C}$
$\text{Phase} = -90^\circ$

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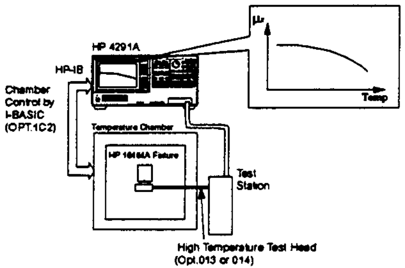
Easy System Integration for Temperature Co-efficient



The HP 4291A provides the following features and options to simplify evaluating temperature characteristics.

1. 1.8 m error-free cables
2. High temperature test head option
3. Built-in HP-IB
4. Optional I-Basic
5. Application Program (I-BASIC)

Tabai Espec Corporation offers a temperature chamber (SU-240-Y) compatible with the HP 4291A for evaluating temperature.

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Ease-of-Use

- HP 4291A opt 002
- Automatic Calculation & Display of Permeability
- No External Computer Needed

The HP 4291A with opt 002 will automatically calculate and display permeability values without using an external computer. This will save you measurement time because the HP 4291A is easy to use.

Note: The HP 4291A with opt 002 can also automatically calculate and display permittivity and loss tangent for dielectric materials.

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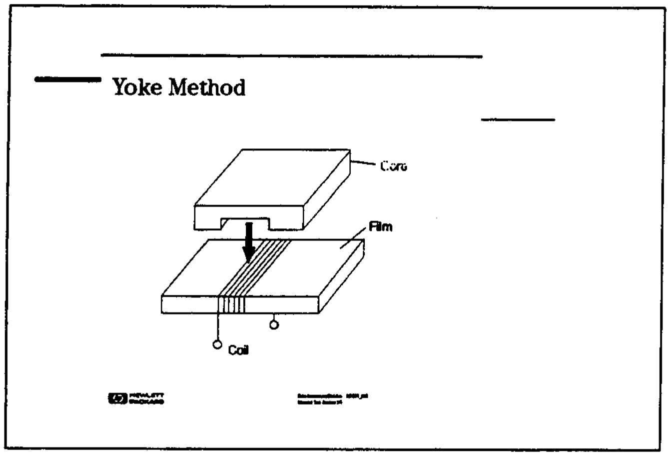
Other Permeability Measurement Techniques

(Addendum)

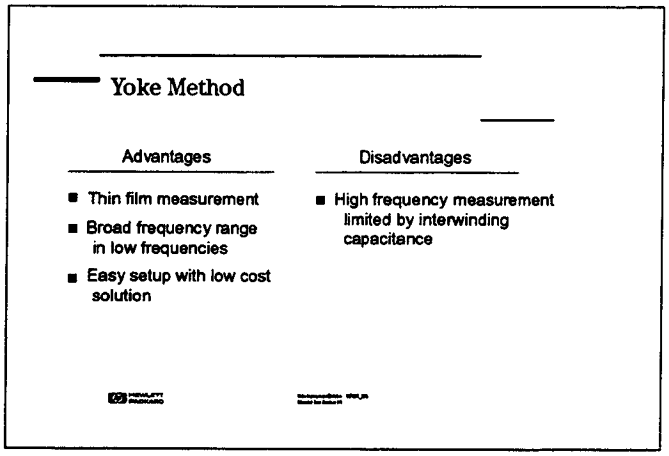
- Yoke
- Differential Coil
- Reflected Wave
- S-Parameter$_{87}$



Yoke Method

In the yoke method, the inductor is wound directly onto a thin film material, and then placed on a core. A high permeability ferrite yoke core is used for this measurement.

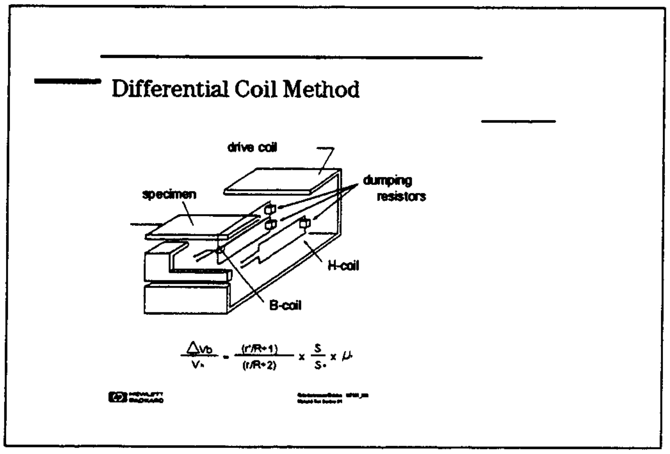
Permeability is calculated from the change of inductance values. Thin film materials can easily measured using this technique. In addition, we can evaluate the surface aeolotropy of the material. The primary disadvantage of this method is the frequency limitation. Again, because of the self-resonance by distributed capacitance, measurements at high frequencies are difficult (its the same situation with the inductor method).



Yoke Method

Advantages	Disadvantages
▪ Thin film measurement	▪ High frequency measurement limited by interwinding capacitance
▪ Broad frequency range in low frequencies	
▪ Easy setup with low cost solution	

Thin film measurements at low frequencies is the unique advantage of the yoke method.

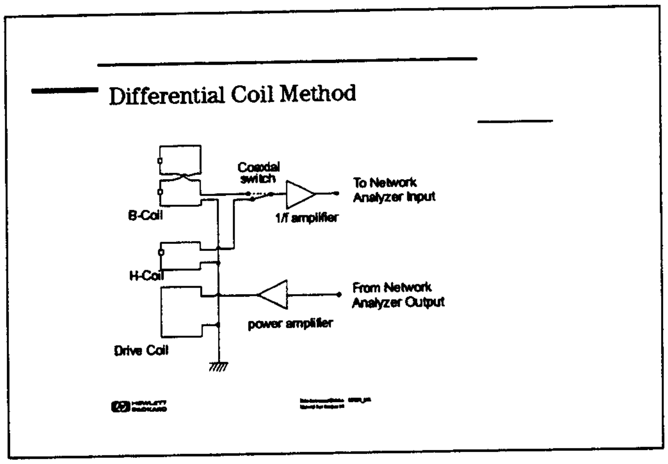


Differential Coil Method

$$\frac{\Delta V_b}{V_h} = \frac{(r'/R+1)}{(r/R+2)} \times \frac{S}{S_o} \times \mu$$

The differential coil method measures the voltages which the magnetic materials induce in the high frequency magnetic fields. The change of induced voltages by materials is detected by a differential coil (B-coil). The magnitude of the applied magnetic fields is detected by the other coil(H-coil). In the loop of these coils, the dumping resistors are series connected to reduce Q and prevent the loop from resonance. This method can measure the permeability of magnetic materials (including thin films at high frequencies). where,

dVb: Increase in voltage when the material is inserted in the loop
Vh: Output voltages of H-coil
r': Dumping resistance of H-coil
r: Dumping resistance of B-coil
R: Input resistance of pre-amplifier
S: Area of the materials
So: Area of H-coil



Differential Coil Method

This is a simple schematic of a differential coil method. The output signal from a network analyzer is amplified to generate magnetic field at the drive coil. The H-Coil monitors the strength of magnetic field which is applied to the B-Coil. The induced voltages are measured at the B-Coil when we put the material under test and when there is no material. The coaxial switch changes the connection to monitor the induced voltages of the H-coil and B-coil.

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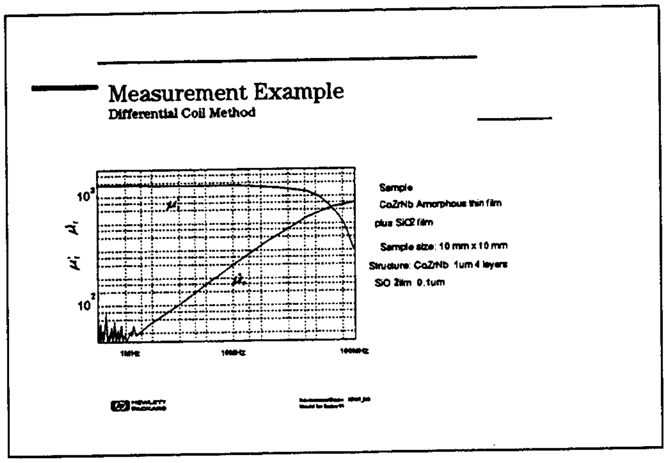

Measurement Example

Differential Coil Method

Sample
CoZrNb Amorphous thin film
plus SiO2 film
Sample size: 10 mm x 10 mm
Structure: CoZrNb 1um 4 layers
SiO 2film 0.1um

This is an example of a thin film magnetic material measurement by the differential coil method. The sample is a CoZrNb Amorphous thin film with an oxidized silicon base.

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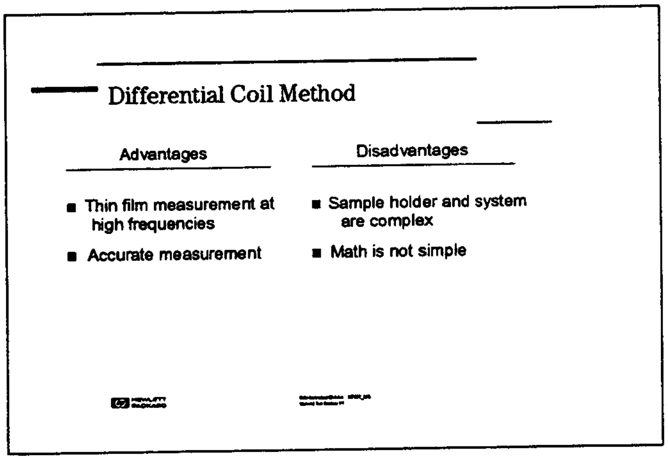

Differential Coil Method

Advantages	Disadvantages
■ Thin film measurement at high frequencies	■ Sample holder and system are complex
■ Accurate measurement	■ Math is not simple

The thin film measurement at high frequencies is the unique advantage of differential coil method.

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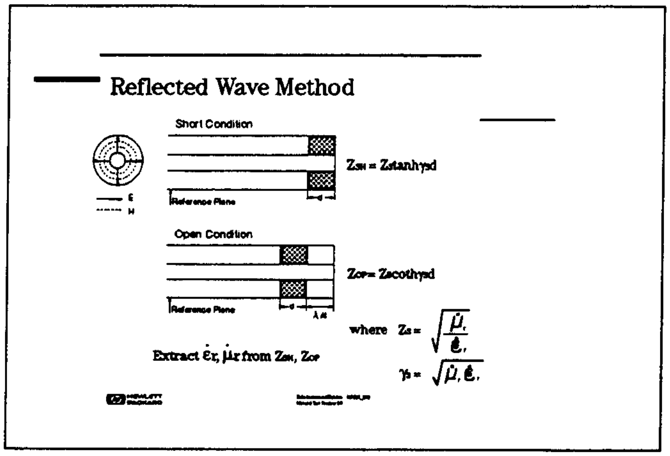

Reflected Wave Method

$Z_{SH} = Z_s \tanh \gamma_s d$

$Z_{OP} = Z_s \coth \gamma_s d$

where $Z_s = \sqrt{\frac{\dot{\mu}_r}{\dot{\varepsilon}_r}}$

$\gamma_s = \sqrt{\dot{\mu}_r \dot{\varepsilon}_r}$

Extract $\dot{\varepsilon}_r$, $\dot{\mu}_r$ from Z_{SH}, Z_{OP}

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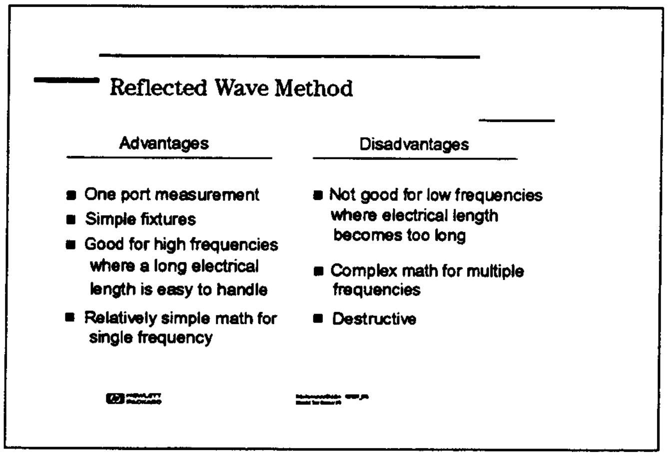
The reflected wave method involves placing the material inside a portion of an enclosed transmission line. The line is usually a section of rectangular waveguide or coaxial airline. In the reflected wave method, the end of the sample is shorted and the input impedance is measured at the reference plane. The sample is moved a quarter of a wave length and the input impedance is measured again. Then the Permittivity and permeability are calculated from the two impedance values.



Reflected Wave Method

Advantages	Disadvantages
■ One port measurement	■ Not good for low frequencies where electrical length becomes too long
■ Simple fixtures	■ Complex math for multiple frequencies
■ Good for high frequencies where a long electrical length is easy to handle	■ Destructive
■ Relatively simple math for single frequency	

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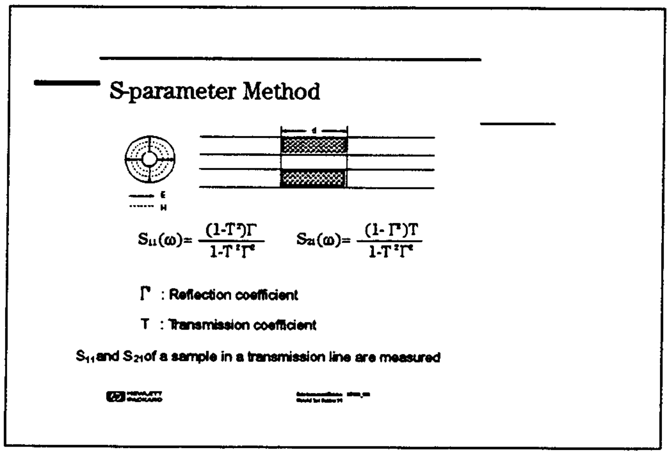

S-parameter Method

$S_{11}(\omega) = \frac{(1-T^2)\Gamma}{1-T^2\Gamma^2}$ $S_{21}(\omega) = \frac{(1-\Gamma^2)T}{1-T^2\Gamma^2}$

Γ : Reflection coefficient

T : Transmission coefficient

S_{11} and S_{21} of a sample in a transmission line are measured

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Permittivity and permeability are computed from the measurements of the reflected signal and transmitted signal in the s-parameter method. The reflection coefficient and the transmission coefficient are derived from the s-parameters, length and the input impedance is measured again. Then the Permittivity and permeability are calculated from the two impedance values.

S-parameter Method

Γ : Reflection coefficient between Zo and Zs when the length of materials is infinitie:

$$\Gamma = \frac{Zs - Zo}{Zs + Zo} = \frac{\sqrt{\frac{\dot{\mu}_r}{\dot{\varepsilon}_r}} - 1}{\sqrt{\frac{\dot{\mu}_r}{\dot{\varepsilon}_r}} + 1}$$

T : Transmission coefficient in the materials (of finite length) and can be described as:

$$T = \exp\left(-j\omega\sqrt{\dot{\mu}\,\dot{\varepsilon}}\,{}^{*}d\right) = \exp\left[-j(\omega/c)\sqrt{\dot{\mu}_r\dot{\varepsilon}_r}\,{}^{*}d\right]$$

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The permittivity and permeability values are calculated from the reflection and transmission coefficients. Here is the equation which is used to derive the permittivity and permeability values.

S-parameter Method

Advantages	Disadvantages
■ Broad frequency range	■ Low frequency limited by length of material
■ Math is straightforward	■ Destructive
■ Gives $\dot{\varepsilon}_r$ and $\dot{\mu}_r$	
■ Simple sample holder	
■ Well suited to microwave measurement	

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