2. Theory

A. System Structure and Working Principle

This system is designed to measure the microwave ferromagnetic resonance of ferromagnetic materials based on a scanning field method, in which the frequency of the applied microwave remains unchanged, while the applied external magnetic field is continuously varied. When the relationship between the external magnetic field and the microwave frequency meets a certain condition, the energy of the RF field is absorbed by the material, a phenomenon called as the ferromagnetic resonance (FMR) of the material.

A schematic diagram of the experimental apparatus is shown in Figure 1.

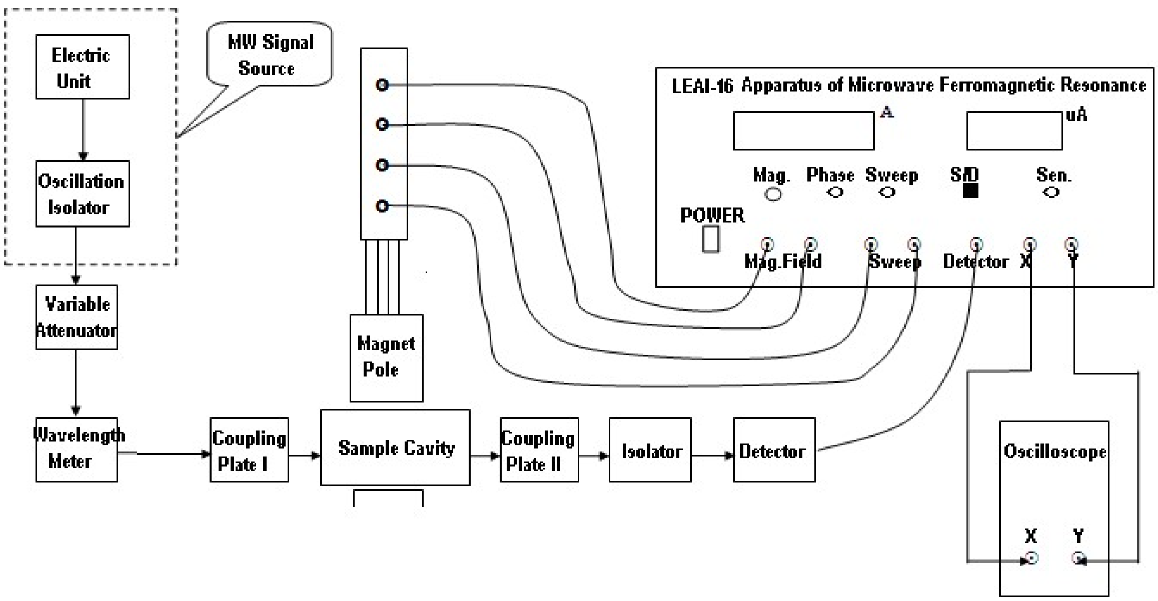

Figure 1 Schematic diagram of experimental system

The system employs a microwave signal of three-centimeter in wavelength to pass through various components of an isolator, a variable attenuator, and a wavelength meter, etc., before entering a sample resonant cavity consisting of a straight rectangular waveguide with coupling plates at each end. When a ferrite material under test is put at the location where the strength of microwave electromagnetic field is maximized in the resonant cavity, a change in resonant frequency and quality factor of the resonant cavity will occur. When the external magnetic field is varied to a certain range, the output power of the microwave will be reduced due to the loss of the sample ferromagnetic resonance. The relationship curve between the output power P of the resonant cavity and the applied magnetic field H can be measured, as shown in Figure 2.

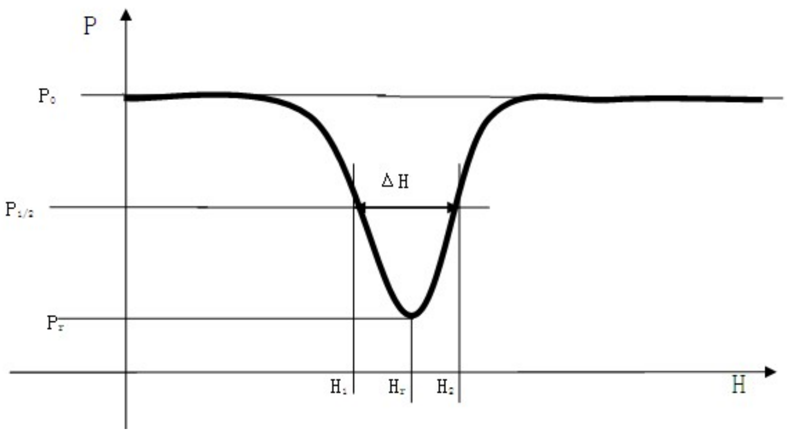

Figure 2 Relationship curve between output power P and applied magnetic field *H*

In Figure 2, P_0 is the initial output power of the cavity while P_r is the output power of the cavity when ferromagnetic resonance occurs with the corresponding external magnetic field H_r called the resonance magnetic field. Under such condition, the imaginary component μ'' of the diagonal element of the tensor permeability $\| \mu \|$ reaches the maximum value μ''_r. According to the ferrite theory, the half resonant point refers to as one-half of the imaginary component of diagonal element of tensor permeability, i.e. $\mu''=\mu''_r/2$. Under such condition, the output power of the resonant cavity $P_{1/2}$ has a relationship with P_0 and P_r as follows:

$$P_{1/2} = \frac{4P_0}{\left(\sqrt{\frac{P_0}{P_r}}+1\right)^2} \tag{1}$$

As shown in Figure 2, *ΔH* is called as the line width of ferromagnetic resonance (FWHM-full width at half maximum), which can be derived from the resonance curve.

Under the ferromagnetic resonance condition, we have $\omega_r=\gamma H_r$. By measuring external magnetic field H_r and microwave frequency ω_r, the gyromagnetic ratio (γ) of the monocrystal sample can be calculated. Then, g-factor (g) can be derived from formula $\gamma=ge/2m_e$, where e and m_e are the charge and mass of an electron, respectively,

After acquiring the relationship curve between output power P and applied magnetic field *H*, the resonance magnetic field *H* and the resonance line width *ΔH* are determined. Furthermore, the relaxation time τ can be estimated by using the formula $\Delta H = 2/\gamma\tau$.

B. Introduction to Microwave and Microwave Devices

(1) Microwave and microwave transmission

Commonly used microwave transmission devices include coaxial waveguide, strip-line, micro-strip line, and so on. A hollow metal tube for guiding electromagnetic wave propagation is called a waveguide with a rectangular cross section shown in Figure 3. From electromagnetic field theory, an electromagnetic wave propagating in free space is transverse electromagnetic (TEM) with the electric and magnetic field lines restricted to directions normal (transverse) to the direction of propagation. Theoretical analysis proves that there are only two types of electromagnetic waves that can exist in waveguides: transversal electric (TE) wave (electric field having only transversal component and magnetic field having longitudinal component); and transversal magnetic (TM) wave (magnetic field having only transversal component and electric field having longitudinal component). In practice, waveguides are usually designed to guide a single waveform only. TE_{10} wave is one of the simplest and the most commonly used waves, also called the primary wave.

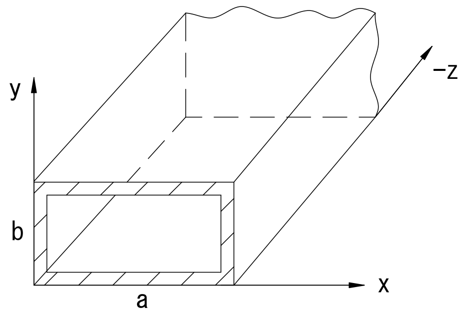

Figure 3 Rectangular waveguide

If a rectangular waveguide has a cross section of $a \times b$, and is filled with a medium of dielectric constant ε and magnetic permeability μ, the propagating components of a TE_{10} wave along Z direction are:

$$E_y = E_0 \sin \frac{\pi x}{a} e^{i(\omega t - \beta z)} \tag{2}$$

$$H_x = -\frac{\beta}{\omega\mu} \cdot E_0 \sin \frac{\pi \cdot x}{a} e^{i(\omega t - \beta z)} \tag{3}$$

$$H_z = i \frac{\pi}{\omega\mu a} \cdot E_0 \cos \frac{\pi \cdot x}{a} e^{i(\omega t - \beta z)} \tag{4}$$

$$E_x = E_z = H_y = 0 \tag{5}$$

where $\omega = \beta \times (\mu\varepsilon)^{-1/2}$ is the angular frequency of the electromagnetic wave, and $\beta = 2\pi/\lambda_g$ is called the phase constant,

$$\lambda_g = \frac{\lambda}{\sqrt{1 - (\lambda / \lambda_c)^2}} \tag{6}$$

λ_g is called waveguide wavelength, $\lambda_c = 2a$ is the cutoff or critical wavelength (a=22.86 mm and b=10.16 mm in this experiment), and $\lambda = c/f$ is the wavelength of the electromagnetic wave in free space.

(2) Microwave devices

a. Solid-state microwave signal source

Two types of microwave oscillators are commonly used, one is the reflex klystron oscillator and the other is a Gunn’s diode oscillator, or known as a solid source.

The core of a Gunn’s diode oscillator is a Gunn’s diode based on the conductive band dual-valley structure (high/low energy valleys) of n-type gallium arsenide. In 1963, Gunn observed that, by applying a DC voltage to the two ends of an n-type gallium arsenide sample, sample current increases with an increase in voltage when voltage is low; however, if the voltage exceeds a critical value, current decreases as voltage increases leading to a negative resistance effect. If the voltage continues to increase ($V>V_b$), the current tends to saturation as shown in Figure 4 indicating an n-type gallium arsenide sample has a negative resistance characteristic.

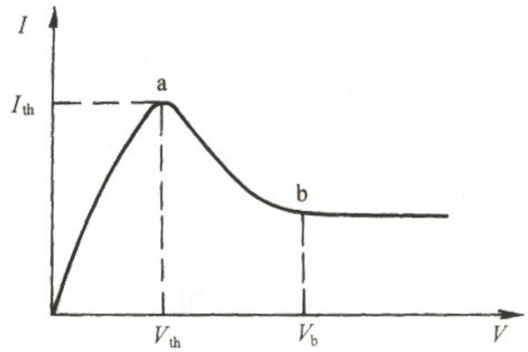

Figure 4 Current-voltage characteristic of Gunn's diode

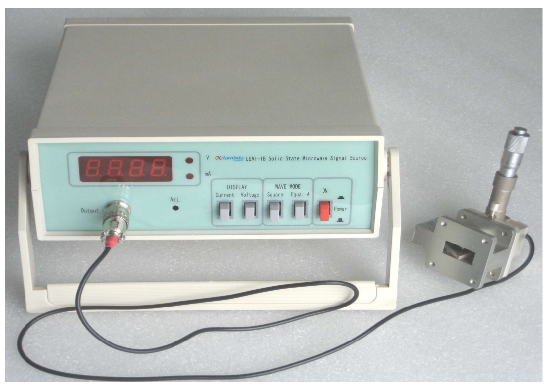

Figure 5 Photo of 3-cm microwave signal source

The solid-state microwave signal source used in this apparatus consists of a host electric unit, an oscillator, and an isolator as seen in Figure 5. The oscillator/isolator unit is connected with the host electric unit through a cable. The Gunn's diode is mounted in the waveguide resonant cavity of TE_{10} mode. By adjusting the micrometer of the oscillator, the insertion depth of the tuning rod into the waveguide cavity can be altered, thereby tuning the resonant frequency of the output microwave. If necessary, by adjusting the tuning screw in the center of the flange in front of the waveguide cavity, optimal coupling between the waveguide cavity and the external waveguide circuit can be achieved. The isolator ensures the matching and isolation between the oscillator and the load, thus enabling stable microwave frequency and power outputs.

The working mode of the oscillator can be selected as either equal-amplitude (Equal A) (i.e. continuous wave) or square wave (Square). Working current or voltage can be alternatively displayed on a 3-1/2 digits meter by pressing down the corresponding button.

Warning: Turn off AC power before connecting/disconnecting any cables to avoid damage to the electric unit.

The frequency of the output microwave can be changed by adjusting the micrometer head. The frequency value can be coarsely determined from the micrometer reading with reference to the "Comparison Table of Frequency-Micrometer Scale" (shown in Appendix). To determine the frequency of the oscillator precisely, an external frequency counter or wavelength meter should be used.

If the microwave output is connected to a microwave detector, by pressing down the "Square" wave mode button, the output waveform of the detector will be square wave when observed on an oscilloscope. If the output waveform is not a regular square wave, use a screwdriver to finely adjust the "Adj." screw on the front panel to achieve a satisfied square-wave output waveform.

Note: optimal square wave has been preset at factory.

b. Isolator

An isolator is an irreversible attenuator whose attenuation is very small in the positive direction (or the transmission direction) at about 0.1 dB or so, but very large in the opposite direction up to dozens of dB. The attenuation ratio of both directions is called isolation. If an isolator is mounted behind a microwave source, it has very little attenuation to the output power but very large attenuation to any reflected waves. Hence, the impact on the frequency and output power of a microwave source due to load variations is eliminated with the use of an isolator.

c. Crystal detector

A point-contact diode (or microwave diode) is used in microwave detection systems with its outer shell made of high frequency aluminum porcelain, as seen in Figure 6. A crystal detector consists of a segment of a waveguide and a microwave diode. Inserting a microwave diode between the two wide walls of a waveguide, the induction voltage between the two leads of the diode can be detected, which is proportional to the electric field strength.

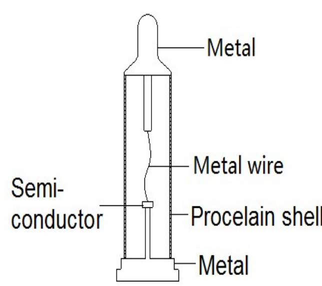

Figure 6 Structure of a crystal detector

d. Frequency meter

An "absorption type" resonance frequency meter is used in this experiment, which contains a hollow cylindrical cavity with a tuning micrometer. The hollow cavity is coupled to a straight waveguide through a hole to form a waveguide branch propagated by the microwave under test. If the cavity of the frequency meter and the straight waveguide mismatch, the electromagnetic field in the cavity is weak and hence the cavity does not absorb microwave power. Under such case, the signal readout at the system terminal remains constant. By adjusting the micrometer to reach a matching state, a portion of the microwave power in the straight waveguide enters the cavity, leading to a decrease in the signal readout at the system terminal. When the detector reaches an absorption peak, the resonant frequency of the cavity is the microwave frequency, which can be determined from the micrometer reading with reference to the “Frequency-Scale Table of 3-cm Cavity Wavelength Meter” (shown in Appendix).

e. Rectangle resonant cavity

A rectangle resonant cavity consists of a rectangle waveguide with metal plates on both ends, called the “coupling plates”. Each metal plate has a small aperture to pass microwave signal to the waveguide path. As the electromagnetic wave in the cavity forms a standing wave, the amplitudes of the electric and the magnetic fields in the resonant cavity follow certain spatial distributions. In this apparatus, a small hole is opened on the narrow side of the cavity to allow any sample to be placed in the cavity. Resonant absorption peak will be observed when the microwave signal frequency matches the resonant frequency of the cavity.

3. Specifications

This experimental system of microwave ferromagnetic resonance works in the three-centimeter band (~ 9370 MHz in frequency). A rectangle resonant cavity is used, so that the whole device structure is simple, clear, and easy to use. A picture of the experimental setup is shown in Figure 7.

Figure 7 Photo of experimental setup

Solid-State Microwave Signal Source:	
Frequency	8.6～9.6 GHz
Frequency drift	≯ $\pm 5\times10^{-4}$/15 min
Output power	> 20 mW under equal amplitude mode
Working voltage	10~14 VDC (typical value + 12 VDC)
Working mode & parameters	Equal amplitude

	Internal square-wave modulation Repetition frequency: 1000 Hz Accuracy: ± 15％ Skewness: ≯ ± 20％
Voltage standing wave ratio	ρ ≯ 1.2
Waveguide dimensions	inner: 22.86 mm × 10.16 mm
Microwave System:	
Sample	1 (mono-crystal)
Microwave frequency meter	range: 8.6 GHz ~ 9.6 GHz
Waveguide dimensions	inner: 22.86 mm × 10.16 mm
Magnetic Field:	
Output voltage and accuracy	Max: ≥ 20 V, 1% ± 1 digit
Output current range and accuracy	0~2.5 A, 1% ± 1 digit
Stability	≤ 1×10^{-3}+5 mA
Sweep Field:	
Output voltage	≥ 6 V
Output current range	0.2 A ~ 0.7 A
Phase shift adjustment	≥ 180°