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MEASURING COMPLEX PERMEABILITY OF FERROMAGNETIC THIN FILM UP TO 10 GHz

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Abstract—The complex permeability of ferromagnetic thin films is measured up to 10 GHz by using shorted microstrip method combining with conformal mapping. The S-parameters are measured by vector network analyzer (VNA), and the effect of the thin film placed both upwards and downwards in the fixture are investigated. The experimental results show that the complex permeability of the thin films is measured accurately from 500 MHz to 10 GHz, and loading the samples with thin film placed downwards can avoid the electromagnetic resonance effectively.

1. INTRODUCTION

With the operating frequency of magnetic materials going higher and some of the applications having reached microwave frequency range [1–5], it is very important to characterize the microwave parameters of the magnetic materials in a reliable way. A number of techniques have been developed for the permeability measurement of materials [6–9]. For the ferromagnetic thin films deposited on the rigid substrates, the shorted microstrip method is usually used, because the samples under test can be easily loaded in the measurement fixture [6]. Some previous works have been done based on analysis and simulation by using plannar transmission line structure [7, 8]. However, because of the high conductivity of the ferromagnetic thin films, the electromagnetic resonance between thin film and ground plane will appear and cause enormous error when the half operating wavelength is equal to the length of the test sample.

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In this paper, the shorted microstrip method is used to measure the complex permeability of the ferromagnetic thin films. The S-parameters are measured by VNA; the effective permeability is deduced from experimental data; and the permeability of ferromagnetic thin film is extracted from effective permeability. The measurement structures with thin film place upwards or downwards are investigated. The experimental results show that the permeability is measured with high accuracy up to 10 GHz, and the resonance between the thin film and the ground plane of the measurement fixture can be avoided successfully by placing the thin film downwards.

2. ANALYSIS

The structure of measurement fixture is shown in Figure 1. The distance between the upper strip and the ground plane is h, the width and thickness of the upper strip are w and t, respectively. When the samples are loaded in the fixture, the multilayer microstrip transmission line is constructed (as shown in Figure 2). And the analysis procedures can be divided into two steps.

2.1. Determine the Effective Permittivity and Permeability

The relationship between transmission constant and experimental S-parameter can be expressed as

$$\gamma^{film} = \gamma^{sub} - \frac{1}{2l} \ln\left(\frac{S_{11}^{film}}{S_{11}^{sub}}\right), \tag{1}$$

where γ^{film} and S_{11}^{film} are the transmission constant and experimental S-parameter with thin film loaded in the fixture; γ^{sub} and S_{11}^{sub} are the

Figure 1. The photograph of measurement fixture.

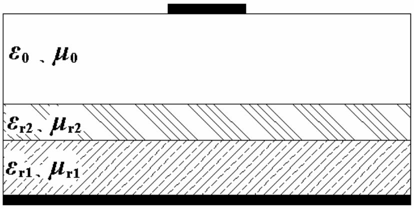


Figure 2. The cross section of multilayer microstrip transmission line.

corresponding parts with only the substrate loaded in the fixture; and l is the length of the sample under test.

Because of the small thickness of thin films, the changes of effective permittivity due to the thin film loaded in the measurement fixture can be ignored [6]. As a result, the effective permeability can be expressed as

$$\mu_{reff} = \left(1 - \frac{1}{2l} \cdot \ln\left(\frac{S_{11}^{film}}{S_{11}^{sub}}\right) \Big/ \left(\gamma_0 \cdot \sqrt{\varepsilon_{reff}}\right)\right)^2, \tag{2}$$

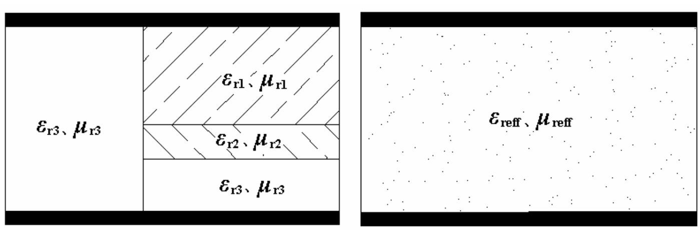
where γ_0 is the transmission constant of air microstrip; μ_{reff} is the effective permittivity of the multilayer microstrip; and ε_{reff} is effective permeability of the multilayer microstrip, which can be obtained from the permittivity of substrate. Since the complex permittivity of the substrate changes little with frequency increasing, the effective permittivity is calculated from the theoretical value of the substrate.

2.2. Analyze the Multilayer Microstrip Transmission Line

The structure shown in Figure 2 can be transferred into the structure shown in Figure 3(a) by using conformal mapping [9], and further more, can be transferred into the structure shown in Figure 3(b) by using equivalent principle [10]. So the effective permittivity can be expressed as [9]

$$\varepsilon_{reff} = 1 - \sum_{i=1}^{3} q_i + \frac{\left(\sum_{i=1}^{3} q_i\right)^2}{\sum_{i=1}^{3} \frac{q_i}{\varepsilon_{ri}}}, \tag{3}$$

where ε_{r1}, ε_{r2} and ε_{r3} are the permittivity of each layer; q_1, q_2 and q_3 are the filling factors corresponding to the layers and can be calculated



(a) (b)

Figure 3. The equivalent structure of the multilayer microstrip transmission line.

from following equations

$$q_1 = \frac{h_1}{2h} \cdot \left[1+\frac{\pi}{4}-\frac{h}{w_{ef}} \cdot \ln\left(2w_{ef} \cdot \frac{\sin\left(\frac{\pi h_1}{2h}\right)}{h_1}+\cos\left(\frac{\pi h_1}{2h}\right)\right)\right], \quad (4)$$

$$q_2 = \frac{h_1+h_2}{2h} \cdot \left\{1+\frac{\pi}{4} - \frac{h}{w_{ef}} \cdot \ln\left[2w_{ef} \cdot \frac{\sin\left(\pi\frac{h_1+h_2}{2h}\right)}{h_1+h_2}+\cos\left(\pi\frac{h_1+h_2}{2h}\right)\right]\right\} - q_1 \quad (5)$$

$$q_3 = 1-\frac{h}{2w_{ef}} \cdot \ln\left(\pi\frac{w_{ef}}{h}-1\right)-q_2-q_1, \quad (6)$$

$$w_{ef} = w+\frac{2h}{\pi} \cdot \ln\left[17.08\left(\frac{w}{2h}+0.92\right)\right] \quad (7)$$

where h_1 and h_2 are the thickness of layer 1 and 2, respectively. For the situation of only substrate loaded in the fixture, layer 1 is substrate, and layer 2 is air. So the effective permittivity can be obtained from Equations (3)–(7).

Then the effective permeability can be deduced from formulation (3) by the duality principle [10] as

$$\frac{1}{\mu_{reff}} = 1-\sum_{i=1}^{3} q_i + \left(\sum_{i=1}^{3} q_i\right)^2 \Bigg/ \left(\sum_{i=1}^{3} q_i\mu_{ri}\right) \quad (8)$$

where μ_{r1}, μ_{r2} and μ_{r3} are the permeability of layer 1, 2 and 3, respectively. As the permeability of air and substrate are both equal to 1, the permeability of thin film can be expressed as

$$\mu_{ri} = \left(\left(\sum_{j=1}^{3} q_j\right)^2 \Bigg/ \left(\frac{1}{\mu_{reff}}-1+\sum_{j=1}^{3} q_j\right)-\sum_{j\neq i}^{3} q_j\right) \Bigg/ q_i, i=1 \text{ or } 2. \quad (9)$$

From Equations (4)–(9) one can see that, for any multilayer microstrip structures, when the width of the upper strip, and the thickness of each layer are known, the relationship between the permeability of thin film and the effective permeability are determined. So the technique is reproducible if geometrical parameters are varied.

3. RESULTS

The ferromagnetic thin films have been measured using the fixture shown in Figure 1. The width of the upper strip (w) is 2 mm. The

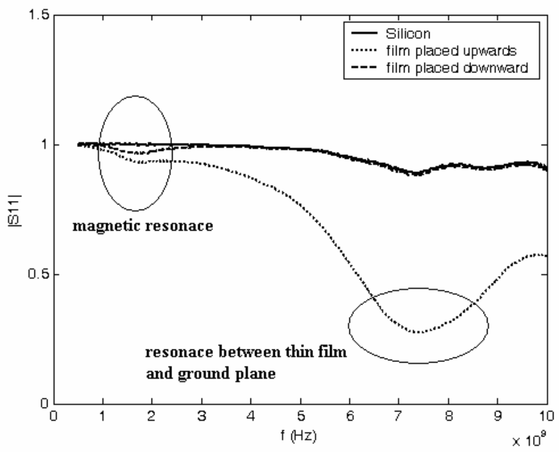


Figure 4. The S-parameters measured by VNA.

distance between upper line and the ground plane (h) is 0.9 mm. The length of the microstrip is 20 mm. The silicon substrate has the size of 7 mm×7 mm×0.53 mm. The following parameters are used for the film deposition: a base vacuum of 2.25×10^{-7} Torr; Ar mixture at pressure of 0.55 mTorr is used as ambient gases; the DC power is 250 W; the sputtering time is 92 seconds; the thickness of the film is found to be 182 nm according to the SEM images of the sample cross section; and the saturated magnetization of the thin film is 1.31×10^{6} A/m. The values of S_{11} when the fixture is loaded with substrate, thin film placed upwards, and thin film placed downwards, are shown in Figure 4. From the results we can see that the magnitudes of S_{11} drops remarkably at 1.7 GHz when the thin film is loaded in the fixture (no matter the thin film placed upwards or downwards). It means that the absorption is caused by ferromagnetic resonance (FMR). At 7.2 GHz, the magnitude of S_{11} drops remarkably only when the thin film is placed upwards, which is caused not by the FMR but by the electromagnetic resonance between thin film and ground plane. The electromagnetic resonance can badly affect the measurement accuracy, so it must be avoided.

The complex permeability of the ferromagnetic thin film has been measured at frequency range up to 10 GHz (shown in Figure 5). Comparing the result of thin film placed upwards with the result of thin film placed downwards, the error of the result with thin film placed upwards increased remarkably due to the electromagnetic resonance. And the results show that, by loading the samples with the thin film placed downwards in the measurement fixture, the resonance between thin film and ground plane can be avoid successfully. That is because

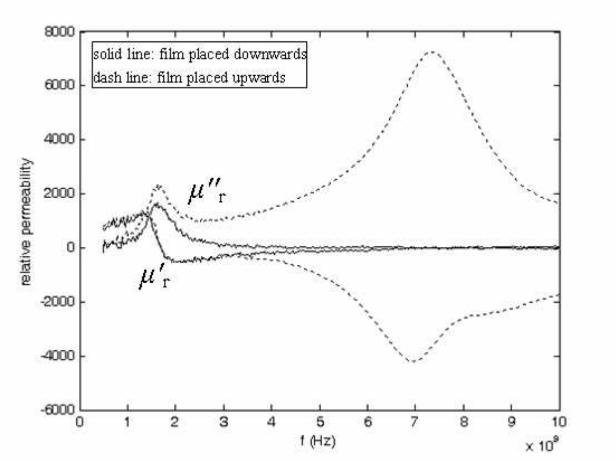


Figure 5. The complex permeability of ferromagnetic thin film.

placing the thin film downwards in the measurement fixture lets the thin film grounded.

Since the analysis model of this technique is multilayer microstrip, the interfaces between the materials is assumed to be smooth. And the effect of the thickness and roughness of the thin film will be studied in the future.

4. CONCLUSION

In this paper, the complex permeability of ferromagnetic thin film is measured from 500 MHz to 10 GHz. Shorted air microstrip structure is used as measurement fixture; VNA is used to detect the perturbation of loading the thin film in the fixture. Multilayer microstrip is analyzed and the relationship equation between the permeability of thin film and the effective permeability has been obtained. The experimental results show that the complex permeability is measured accurately in the whole interested frequency band, and by placing the thin film downwards in the measurement fixture, the resonance between thin film and ground plate can be avoid effectively.

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