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CHARACTERIZATION OF ELECTROMAGNETIC PROPERTIES BY SIMULATIONS USING THE DOUBLE-RIDGED CAVITY

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ABSTRACT

Cavity method is widely used in microwave measurement of electromagnetic properties. In this paper, a new double-ridged cavity method is proposed, which can enhance the operational frequency bandwidth. Building on the perturbation theory, the measurement equations required for permittivity and permeability extraction are developed. And for obtaining the electromagnetic properties more accurately, a calibration method is introduced to calibrate the shape factors. The proposed method is first simulated using the High Frequency Structure Simulator (HFSS) to demonstrate the linear relationship between the resonant parameters and the electromagnetic properties. Thereafter, a series of standard samples are also tested and verified by using the numerical simulator. For comparison the reference data, the calibration method can obviously improve the accuracy of electromagnetic parameters, especially the imag part error of complex permeability, which is reduced from more than 60% to about 4%.

Keywords: double-ridged cavity, electromagnetic properties, calibration method

NOMENCLATURE

ε'	real part of complex permittivity
ε''	imag part of complex permittivity
μ'	real part of complex permeability
μ''	imag part of complex permeability

1. INTRODUCTION

With the development of RF and microwave technology, there is a huge demand to characterize the electromagnetic parameters of the materials. The measurement methods are mainly including two categories [1]: non-resonant method, just like free-space method, transmission method and so on, and resonant method. The resonant techniques are usually using the different kinds of resonance structures to determine the complex permittivity and permeability, which according to the shift of the resonant f and quality factor Q, before and after the insertion the MUT (materials under test). To enhance the operational bandwidth of the cavity, Hyde [2], et al. first present the dual-ridged waveguide for broadband characterization of materials, using a transmission/reflection material characterization technique measured scattering parameters and achieved the measurement of electromagnetic parameters. And then, Kik [3] building on the perturbation theory developed double-ridged cavity and measured the complex permittivity of three common plastic specimens.

In this research, a wideband double-ridged cavity is studied and a calibration method is proposed to give more accurate measurement. Utilizing the numerical emulator HFSS, a number of sample were measured. According to the simulation results, it can be found that the calibration results are in good agreement with the reported data.

2. THEORETICAL CONSIDERATIONS

To improve the measurement frequency range, the double-ridged cavity is analyzed. Using the similar procedure to [Complex Permittivity Measurement Using a Ridged Waveguide Cavity and the Perturbation Method, Ridge Waveguides and Passive Microwave Component] to drive the electromagnetic fields distribution inside the empty cavity. Only the necessary parts of the derivation are presented here. However, the cross section of the double-ridged cavity is irregular, so it is divided into gap region (with red marked) and trough region (the remaining area), as shown in Fig.1.

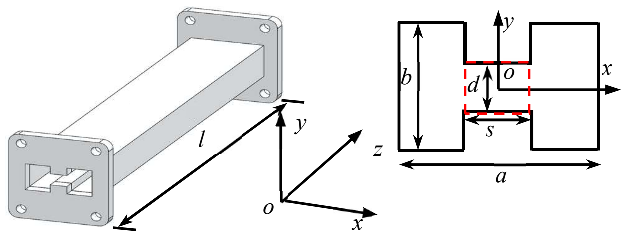

FIGURE 1: SCHEMATIC OF SIMULATION MODEL OF DOUBLE-RIDGED CAVITY AND THE COORDINATE SYSTEM.

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The TE_{10} mode is the resonance of the domain mode inside the double-ridged cavity, and the general expression of the TE_{10p} mode can be derived to the following field components [3,4]:

In the gap region:

$$
\begin{aligned}
&E_z = 0 \\
&E_y = \omega\mu_0 \cos\left(\frac{\pi}{2} - \frac{\pi x}{2a}\right)\sin\left(\frac{p\pi}{l}z\right) \\
&H_x = -\frac{1}{\omega\mu_0}\frac{p\pi}{l}\cos\left(\frac{\pi}{2} - \frac{\pi x}{2a}\right)\cos\left(\frac{p\pi}{l}z\right) \\
&H_z = \mathrm{j}\frac{1}{\omega\mu_0}\frac{\pi}{a}\frac{p\pi}{l}\sin\left(\frac{\pi}{2} - \frac{\pi x}{2a}\right)\sin\left(\frac{p\pi}{l}z\right)
\end{aligned}
\tag{1}
$$

In the trough region:

$$
\begin{aligned}
&E_x = E_z = H_y = 0 \\
&E_y = -\omega\mu_0 \frac{\pi}{a}\sin\left(\frac{\pi}{a}x\right)\sin\left(\frac{p\pi}{l}z\right) \\
&H_x = \left(\frac{1}{\omega\mu_0}\frac{\pi}{a}\right)\left(\frac{p\pi}{l}\right)\sin\left(\frac{\pi}{a}x\right)\cos\left(\frac{p\pi}{l}z\right) \\
&H_z = \left(\frac{-\mathrm{j}k_T^2}{\omega\mu_0}\right)\cos\left(\frac{\pi}{a}x\right)\sin\left(\frac{p\pi}{l}z\right)
\end{aligned}
\tag{2}
$$

where p is the number of half-wave variations of the field along z-direction, $k_T^2 = k_x^2 + k_y^2$,which is the transverse components of the wave number.

For complex permittivity measurement, the MUT are placed horizontally in the E-plane of the double-ridged cavity with the odd mode, *viz* p=1,3,5…. However, for complex permeability measurement, the MUT are placed horizontally in the H-plane of the double-ridged cavity with the even mode, *viz* p= 2,4,6…. Moreover, using the general expression of the perturbation formulation to calculated the electromagnetic parameters, which can be written as the following [1]:

$$
\frac{\omega - \omega_0}{\omega_0} = -\frac{\iiint_{V_S}\left(\Delta\varepsilon \vec{E}_0^* \cdot \vec{E}_s + \Delta\mu \vec{H}_0^* \cdot \vec{H}_s\right)dv}{\iiint_{V_C}\left(\varepsilon_0 \vec{E}_0^* \cdot \vec{E}_0 + \mu_0 \vec{H}_0^* \cdot \vec{H}_0\right)dv}
\tag{3}
$$

where V_s and V_c are the volume of the MUT and the cavity, respectively, $\Delta\varepsilon$ and $\Delta\mu$ are the changes in the complex permittivity and permeability of the MUT in the cavity.

After some mathematic manipulations by using the formula (1) to (3), the equations for the complex permittivity and permeability of the MUT can be written as:

$$\varepsilon' = 2\beta_e \frac{f_0 - f_s}{f_0} + 1 \tag{4}$$

$$\varepsilon'' = \beta_e\left(\frac{1}{Q_s} - \frac{1}{Q_0}\right) \tag{5}$$

$$\mu' = 2\beta_h \frac{f_0 - f_s}{f_0} + 1 \tag{6}$$

$$\mu'' = \beta_h\left(\frac{1}{Q_s} - \frac{1}{Q_0}\right) \tag{7}$$

With the shape factors are defined as:

$$\beta_e = \frac{\iiint_{V_C}\left|\vec{E}_0\right|^2 dv}{\iiint_{V_S}\vec{E}_0^* \cdot \vec{E}_s dv} \tag{8}$$

$$\beta_h = \frac{\iiint_{V_C}\left|\vec{H}_0\right|^2 dv}{\iiint_{V_S}\vec{H}_0^* \cdot \vec{H}_s dv} \tag{9}$$

where f and Q are the resonant frequency and the quality factor, the subscript 0 represents the unloaded and s represents the load. Otherwise, the shape factor β_e and β_h can be determined by using the sample of know the electromagnetic parameters.

3. RESULTS AND DISCUSSION

In this work, we use the HFSS to build the simulation model and measure the electromagnetic parameters of MUT. The geometrical parameters of the double-ridged cavity are shown in Table 1.

Table 1 The geometrical parameters of double-ridged cavity

Cavity type	a / mm	b / mm	s / mm	d / mm	l / mm
WRD475	27.69	12.85	6.91	5.46	190.00

In order to simulate the real experiment condition, the wall of the cavity is selected as brass instead of PEC (Perfect Electric Conductor), and chosen air instead of vacuum as the medium inside the cavity. Moreover, the radius of the MUT is 2mm.

Fig.2 shows the all TE_{10p} resonant mode in the operated band of the WRD475 cavity. According to the theoretical calculation, the modes from left to right are TE_{104} to TE_{1013}, respectively. But in this work, we chose TE_{1010} mode to measure the complex permeability, whose resonant frequency f_0 is 8.7905GHz and quality factor Q_0 is 4062.8, otherwise, using the TE_{1011} mode to measurement the complex permittivity, whose resonant frequency f_0 is 9.5131GHz and quality factor Q_0 is 4341.9.

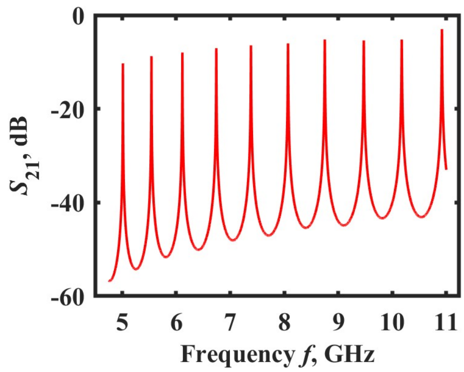

FIGURE 2: RESONANT MODES OF THE ENTIRE FREQUENCY BAND IN THE WRD475 DOUBLE-RIDGED CAVITY.

To check the validity of the calibration method, the electromagnetic parameters of the MUT are varied in a wide range, such as the ε' is varied from 1 to 10 with a fine step width of 1 while the ε'' is a constant of 0.02; the ε'' is varied from 0.05 to 0.5 with a fine step width of 0.05 while the ε' is a constant of 5. As for the complex permeability, it is kept the same variation of the complex permittivity. The resonant frequency f and quality factor Q are calculated according to the setup as: the peak point

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of the S_{21}-parameter curve is considered as the f, the Q is obtained using the 3-dB bandwidth method.

According to the fitting curves plot in Fig.3, there is a strong linear relationship between the resonance parameters (f and $1/Q$) and the electromagnetic characteristic (ε', ε'', μ' and μ''), and all the goodness of fit are great than 0.9.

Furthermore, for quantifying the accuracy of the double-ridged cavity method, a serious of MUT with know the complex permittivity or permeability from HFSS material library and literatures[5-7] were selected to carry out numerical simulation. The simulation results were listed in the Table2 and Table3.

According to Table2 and Table3, it can be observed that using the calibration method the obtained complex permittivity and permeability results of the MUT are in good agreement with the reference data, and the measurement error is obviously reduced.

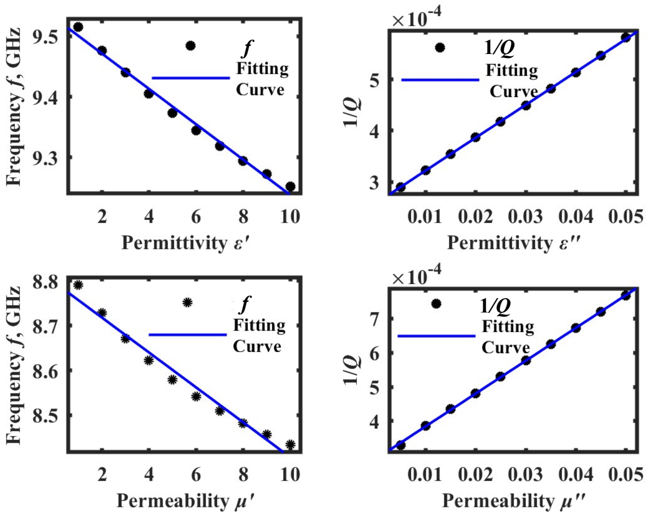

FIGURE 3: THE FITTING CURVE OF NUMERICAL SIMULATION RESULTS.

4. CONCLUSION

This paper presented a new resonant cavity based on double-ridged waveguide. From the theoretical analysis and the electromagnetic simulation, we find that there is a strong linear relationship between the resonant characteristic of the double-ridged cavity and the electromagnetic parameters of the MUT. Thereafter, the cavity was calibration with the sample which is known the electromagnetic parameters. According to the simulation results, it was verified that the measurement accuracy has been significantly improved with shape factor calibration, especially the imag part error of complex permeability, which is reduced from more than 60% to about 4%. As a future work, we will focus on the experimental measurement of electromagnetic parameters.

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Table 2 Measurement of complex permittivity at centre of the double-ridged cavity of operating mode TE_{1011}, which f_0=9.5131GHz, Q_0=4341.9

Material	f / GHz	Q	Reference		Before calibration				After calibration			
					Permittivity		Error%		Permittivity		Error%	
			ε_0'	ε_0''	ε_b'	ε_b''	ε_b'	ε_b''	ε_a'	ε_a''	ε_a'	ε_a''
Teflon	9.4671	4289.9	2.10	4.20e-4	--	--	--	--	--	--	--	--
Rogers O3203	9.4355	3750.6	3.02	4.83e-3	2.43	3.2e-3	19.53	33.75	2.98	4.4e-3	1.32	8.94
Rogers RT5870	9.4612	3961.6	2.33	2.79e-3	1.95	1.9e-3	16.31	31.90	2.32	2.7e-3	<1	3.43
Taconic TLX	9.4525	3667.4	2.55	4.84e-3	2.11	3.7e-3	17.25	23.55	2.47	4.8e-3	3.14	<1

Table 3 Measurement of complex permeability at centre of the double-ridged cavity of operating mode TE_{1010}, which f_0=8.7905GHz, Q_0=4062.8

Material		f / GHz	Q	Reference		Before calibration				After calibration			
						Permittivity		Error%		Permittivity		Error%	
				μ_0'	μ_0''	μ_b'	μ_b''	μ_b'	μ_b''	μ_a'	μ_a''	μ_a'	μ_a''
Co2U12 Hexaferrite/ Epoxy compisite	40/60	8.7744	299.4	1.24	0.2108	--	--	--	--	--	--	--	--
	50/50	8.7739	442.3	1.25	0.137	1.095	0.051	12.40	62.77	1.25	0.132	<1	4.00
	70/30	8.7700	426.8	1.31	0.144	1.117	0.053	14.73	63.19	1.30	0.137	<1	4.64
CI/Si-rubber		8.7737	314.7	1.25	0.200	1.096	0.074	12.32	63.00	1.25	0.192	<1	3.95
CI/epoxy composite		8.7766	214.1	1.20	0.300	1.080	0.111	10.00	63.00	1.21	0.290	<1	3.37

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