Relative Permittivity Measurements using the Higher-order Resonant Modes of a Near-field Microwave Probe[1]

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Abstract

We demonstrate that the higher-order resonant modes of a near-field microwave probe can be used to quantitatively measure the relative permittivity of low-loss dielectric materials, thereby broadening the frequency range of the technique. In order to assess the accuracy of the near-field probe measurements, we compare with relative permittivity measurements performed with both split-post and split-cylinder resonators.

1. Introduction

Near-field microwave probe methods have emerged as an important tool for measuring the high-frequency electrical properties of dielectric films [1, 2]. In these cases, where the film's thickness can be orders of magnitude smaller than the wavelength, conventional cavity techniques do not have the necessary resolution or sensitivity. However, the resolution of near-field probes is determined by the dimensions of the probe tip, not the wavelength, so such probes are able to measure the dielectric properties of thin films.

In this paper, we report relative permittivity measurements for several well known, low-loss dielectric materials using a near-field probe that employs a coaxial resonator. However, instead of using only the lowest-order resonance of the near-field probe, we also performed measurements with a higher-order resonant mode in order to broaden the frequency range of this method. This is important as, in general, the relative permittivity of dielectric materials are frequency dependent. To assess accuracy of these relative permittivity measurements, we compared with measurements made with a split-post resonator [3] and a split-cylinder resonator [4].

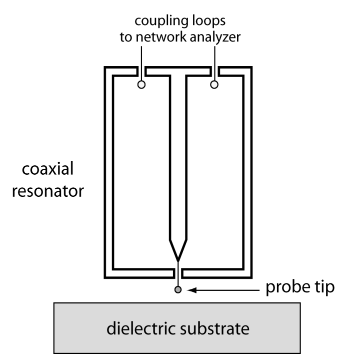

Figure 1: Cross-section of the near-field microwave probe.

2. Near-Field Microwave Probe System

A cross section of the near-field microwave probe system is shown in Figure 1. The probe consists of an $n\lambda/4$-wavelength coaxial transmission-line resonator suspended above the dielectric substrate under test. The

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center conductor of the coaxial resonator transitions to a thin wire that is terminated in a spherical tungsten tip, whose diameter is approximately 200 μm. The gap between the evanescent microwave probe and the dielectric sample is varied through a motorized positioner. To excite a TEM resonance in the near-field probe, two small coupling loops, which are connected to the ports of a network analyzer, are placed near the top of the coaxial resonator.

At a sufficient distance between the near-field probe and the dielectric sample, there is no interaction between the dielectric material and the electrical charges present on the probe's spherical tip, so that the resonant frequency of the near-field probe is not affected. However, as the probe approaches the dielectric surface, the charges on the sphere are redistributed due to its interaction with the dielectric material, resulting in a change in the local electric field and a slight, but measurable, decrease in the resonant frequency of the coaxial resonator. As shown in Fig.2, the measured resonant frequency shift becomes more pronounced as the gap between probe tip and the dielectric decreases. Not only is the shift in resonant frequency a function of the gap between the probe tip and the dielectric material, but it also depends on the relative permittivity of the dielectric.

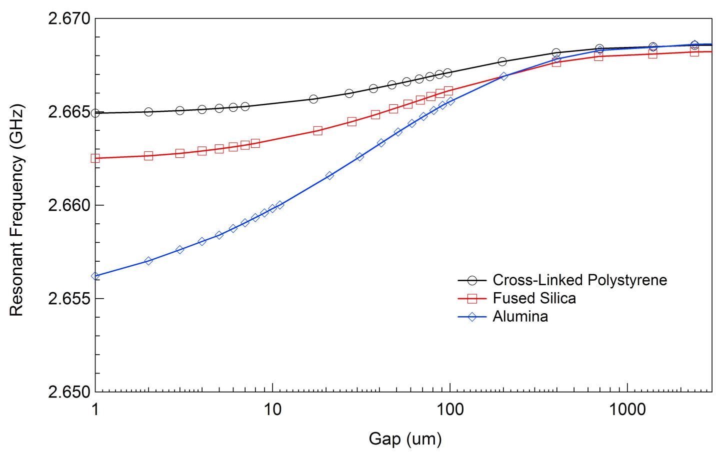

Figure 2: Near-field probe resonant frequency as a function of gap.

3. Near-Field Probe Model

In order to calculate the relative permittivity of the dielectric material, we must first accurately model how the near-field probe's resonant frequency is affected by the probe/sample gap and the relative permittivity of the dielectric. To simplify the analysis, several assumptions are made, as outlined in the model proposed by Gao in [1]. First, since the shift in the probe's resonant frequency Δf_0 is small relative to the resonant frequency f_0, we can use the following perturbation formula common for resonant cavities:

$$\frac{\Delta f_0}{f_0} = \frac{\int_V \Delta\epsilon E_1 \cdot E_0 \; dv}{\int_V \epsilon_0 E_0 \cdot E_0 \; dv}, \tag{1}$$

where E_1 is the electric field for the case of the probe suspended at a distance g above a dielectric half-plane of relative permittivity $\epsilon_r^{'}$, E_0 is the electric field for the case of the probe in free space, and $\Delta\epsilon = \epsilon_r^{'} - 1$. Note that the material is assumed to be nonmagnetic ($\mu_r^{'}$=1). In order to calculate the electric fields E_0 and E_1, we assume that since the change in electric field is localized to the near-field region of the tip and dielectric sample, and this region is much smaller than the wavelength, we can use the quasi-static method of images to determine the electric field. As outlined in [1], for the case where the probe tip is in contact with the dielectric material, (1) reduces to

$$\frac{\Delta f_0}{f} = A\left[1 + \frac{\ln(1-b)}{b}\right], \tag{2}$$

where

$$A = \frac{16 R_0 \ln(\frac{R_2}{R_1})}{\lambda} \tag{3}$$

and

$$b = \frac{\epsilon_r^{'} - 1}{\epsilon_r^{'} + 1}. \tag{4}$$

For the constant A in (3), R_0 is the radius of the spherical probe tip, and R_2 and R_1 are the outer and inner radii of the coaxial resonator conductors.

4. Permittivity Measurements

In previous work [1], Gao used only the fundamental resonance of the coaxial resonator when performing dielectric measurements. Here, in order to broaden the frequency range of this method, we use both the fundamental and one of the higher-order TEM resonant modes of the coaxial resonator. To validate that the higher-order modes can be used, we measured the permittivities of several dielectric materials and compared them to data obtained with both the split-post [3] and split-cylinder [4] cavities.

For each material, we positioned our near-field probe above the dielectric substrate at a height where there was no interaction between the probe and the substrate, usually at a height greater than 5 mm. Then, with the network analyzer connected to the two coupling loops of the coaxial resonator, we excited a TEM resonant mode. The fundamental mode occurred at approximately 2.7 GHz, while the higher-order mode was at 7.5 GHz. For both resonances, we used the method described in [5] to measure the resonant frequency. Next, we incrementally decreased the gap between the near-field probe and measured the resonant frequency of both modes, as shown in Fig. 2. We continued this process until we achieved "soft contact", a term used by Gao in [1] to designate when the probe is contacting the surface of the substrate, but the contact is such that the near-field probe is neither distorted nor damaged. With our specific system, we were able to position the probe to within 1 μm of the dielectric. At this position, the shift in resonant frequency Δf_0 was calculated from Eq. (2) for both the fundamental and higher-order TEM resonant modes.

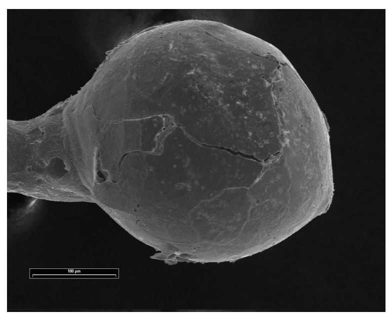

Figure 3: Image of probe tip obtained from scanning electron microscope.

In order to use Eq. (2) to calculate the relative permittivity of the substrate, we must first determine the value of the constant A. In Eq. (3), note that A could be determined from the resonant frequency and the dimensions of the coaxial resonator and spherical probe tip. However, as shown in the scanning electron microscope image of Fig. 3, the probe tip is not perfectly spherical. Therefore, as in [1], we treated A as a calibration constant that was determined from a measurement Δf for a dielectric whose relative permittivity was known. In our case, we measured our reference dielectric with both the split-post and split-cylinder cavities, which are nondestructive techniques for accurately characterizing dielectric substrates.

Table 1: Comparison of relative permittivity measurements of several dielectric materials between the evanescent microwave probe and the split-post and split-cylinder resonators. In this series of measurements, a fused silica substrate ($\epsilon_r^{'} = 3.83$) was used to calibrate the probe.

Material	Near-Field Probe				Split-Post Cavity		Split-Cylinder Cavity	
	f(GHz)	$\epsilon_s^{'}$	f(GHz)	$\epsilon_s^{'}$	f(GHz)	$\epsilon_s^{'}$	f(GHz)	$\epsilon_s^{'}$
Cross-Linked Polystyrene	2.667	2.6	7.752	2.5	3.353	2.53 ± 0.01	9.757	2.55 ± 0.03
1723 Glass	2.662	6.0	7.721	5.8	3.308	6.15 ± 0.03	8.764	6.17 ± 0.02
Aluminum Nitride	2.660	8.2	7.704	8.5	3.279	8.44 ± 0.04	8.134	8.43 ± 0.02
Alumina	2.658	9.4	7.699	9.4	3.279	10.03 ± 0.05	8.136	10.07 ± 0.03

Table 2: Comparison of relative permittivity measurements of several dielectric substrates between the evanescent microwave probe and the split-post and split-cylinder resonators. In this series of measurements, an aluminum nitride substrate ($\epsilon_r^{'} = 8.44$) was used to calibrate the probe.

Material	Evanescent Microwave Probe				Split-Post Resonator		Split-Cylinder Resonator	
	f(GHz)	$\epsilon_s^{'}$	f(GHz)	$\epsilon_s^{'}$	f(GHz)	$\epsilon_s^{'}$	f(GHz)	$\epsilon_s^{'}$
Cross-linked Polystyrene	2.667	2.6	7.752	2.6	3.353	2.53 ± 0.01	9.757	2.55 ± 0.03
Fused Silica	2.665	3.9	7.736	3.8	3.341	3.82 ± 0.02	9.012	3.83 ± 0.02
1723 Glass	2.662	6.0	7.721	5.8	3.308	6.15 ± 0.03	8.764	6.17 ± 0.02
Alumina	2.658	9.7	7.699	9.3	3.279	10.03 ± 0.05	8.136	10.07 ± 0.03

In this way, we performed dielectric measurements for five dielectric materials: cross-linked polystyrene, fused silica, 1723 glass, aluminum nitride, and alumina. In Table 1, we report the measured relative permittivity for these materials using both the fundamental and higher-order resonant mode of the near-field probe. In this case, we used the fused silica substrate as the reference dielectric to calibrate the near-field probe. For comparison, we also show relative permittivity results for the same materials measured with the split-post and split-cylinder cavities. In a similar way, we report in Table 2 the relative permittivity measurements for the same materials, except that the aluminum nitride substrate was used as the dielectric reference for the near-field probe calibration.

For both sets of measurements, we see good agreement between most of the near-field probe measurements and those performed with the split-post and split-cylinder resonators. This is the case both for the fundamental and the higher-order TEM resonant modes of the coaxial resonator. However, there is a small systematic bias in the results due to the fact that we were limited in our ability to position the probe at the surface of the dielectric without damaging or distorting the probe. In all cases, our probe was positioned less than 1 μm from the dielectric, resulting in a slightly smaller shift in resonant frequency than would have occurred if the probe were in direct contact. In the future, once we incorporate a piezoelectric stage in our system, we would expect to have better control over the probe position, and this systematic error would be reduced considerably.

5. Summary

We showed that the frequency range of the near-field microwave probe method can be broadened by using higher-order resonant modes in addition to the fundamental mode of the coaxial resonator. Comparisons of relative permittivity measurements of a range of dielectric materials show good agreement between the near-field probe measurements and those performed with split-post and split-cylinder resonator methods.

Acknowledgments

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References

[1] C. Gao and X.-D. Xiang, Rev. Sci. Instrum., vol. 69, no. 11, p. 3846, 1998.

[2] Z. Wang, M. A. Kelly, Z. Shen, and J. Wetzel, J. Appl. Phys., vol. 92, no. 2, p. 808, 2002.

[3] J. Krupka, R. Geyer, J. Baker-Jarvis, and J. Ceremuga, in Seventh International Conference on Dielectric Materials, Measurements and Applications, September 1996, pp. 21–24.

[4] M. Janezic, E. Kuester, and J. Baker-Jarvis, in IEEE MTT-S International Microwave Symposium Digest, June 2004, pp. 1817–1820.

[5] K.J. Coakley, J.D. Splett, M.D. Janezic, and R.F. Kaiser, in IEEE Transactions on Microwave Theory and Techniques, vol. 51, no. 3, March 2003, pp. 862–868.