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Developments in techniques to measure dielectric properties of low-loss materials at frequencies of 1–50 GHz

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Abstract

Recent developments in precise measurement methods of the complex permittivity of low and medium loss dielectrics are presented. In particular TE_{01} mode dielectric resonator, whispering gallery mode resonator (WGMR) and split post dielectric resonator techniques are discussed. It is shown how to optimize the size of metal shield of the TE_{01} mode dielectric resonator to minimize conductor losses to obtain the highest sensitivity of loss tangent measurements. Conductor and radiation loss limits are discussed for open and closed whispering gallery mode resonators. New constructions of split post dielectric resonators are presented for dielectric measurements at frequencies from 25 to 35 GHz and for measurements of ferroelectrics.

Keywords: Test methods; Dielectric properties; Dielectric measurements; Resonators

1. Complex permittivity measurements employing $TE_{01\delta}$ mode dielectric resonators

Resonant techniques employing cavities and dielectric resonators provide the highest measurement accuracy for determining the complex permittivity of low-loss dielectric materials at microwave frequencies. The most important criteria for choice of a specific measurement fixture are measurement uncertainty of real permittivity and measurement sensitivity of the dielectric loss tangent. Real permittivity measurement uncertainty depends on several factors namely: uncertainties in physical dimensions of the sample under test and resonant structure, computational inaccuracies, and in some cases presence of air gaps between the sample and the cavity walls. For the most accurate measurement techniques uncertainty of the physical dimensions of the sample under test should constitute the dominant part of the uncertainty of real permittivity. When the electric field for specific modes is continuous across a sample boundary, such as for $TE_{01\delta}$ modes in cylindrical samples shielded by cylindrical metal cavity (Fig. 1), high measurement accuracy of real permittivity and high resolution of the dielectric loss tangent are achieved.[1,2] Using $TE_{01\delta}$ dielectric resonator technique it is possible to measure real permittivity with accuracy about 0.2%.[3]

Sensitivity of the dielectric loss measurements using the $TE_{01\delta}$ dielectric resonator (as well as all other resonant techniques) is related to the presence of parasitic losses like conductor losses, dielectric losses and radiation losses. The highest sensitivity of dielectric loss measurements can be obtained if parasitic losses are minimized.

For arbitrary resonant technique the dielectric loss tangent of the sample under test δ_r can be determined using the following formulae

$$\tan\delta_r = \left(Q_u^{-1} - p_{es}\tan\delta_{sr} - R_S/G - Q_r^{-1}\right)/p_{er} \tag{1}$$

where Q_u—measured, unloaded Q-factor of the resonant structure; Q_r—Q-factor due to radiation; and δ_{sr}—loss tangent of a dielectric support; and R_S—surface resistance of the a metal shield; and G—geometric factor defined as:

$$G = \frac{\omega \int\int\limits_V\int \mu_0 |\mathbf{H}|^2 \mathrm{d}v}{\oint\!\!\!\oint\limits_S |\mathbf{H}_\tau|^2 \mathrm{d}s} \tag{2}$$

$p_{es(r)}$—electric energy filling factor for the dielectric support (s) and the sample under test (r)

$$p_{es(r)} = \frac{W_{Es(r)}}{W_{ET}} = \frac{\int\int\limits_{V_s}\int \varepsilon_{s(r)} \mathbf{E}\cdot\mathbf{E}\mathrm{d}v}{\int\int\limits_V\int \varepsilon(v) \mathbf{E}\cdot\mathbf{E}\mathrm{d}v}. \tag{3}$$

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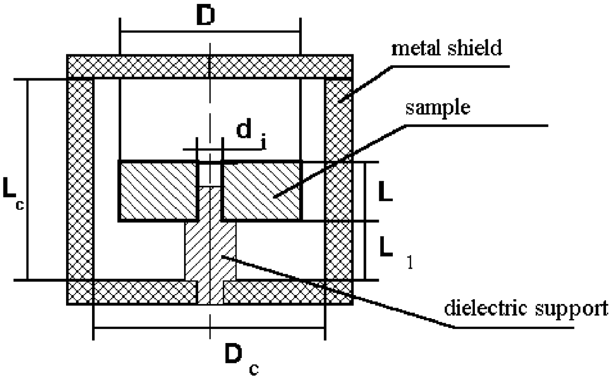

Fig. 1. Schematic diagram of a $TE_{01\delta}$ mode dielectric resonator.

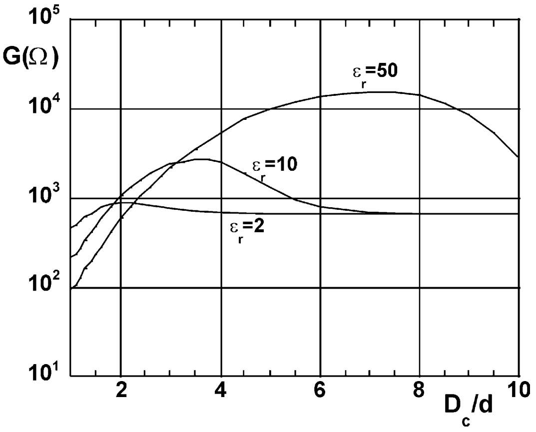

Fig. 2. Geometric factor versus size of metal enclosure for quasi $TE_{01\delta}$ mode dielectric resonator having $D/L = D_c/L_c = 2$.

It is clear from Eq. (1) that minimum parasitic losses can be achieved if geometric factor value and Q-factor due to radiation approach maxima. For close resonant structure radiation losses are not present so the geometric factor value should be as large as possible which takes place if the sample is situated away from the metal shield, preferably at the center of the cavity. As it has been already proved in an earlier paper[3] geometric factor values vary with size of metal shield and permittivity as presented in Fig. 2.

Assuming a size of the dielectric sample close to optimum, one can evaluate that loss tangent resolution can be as low as 1×10^{-7} for high permittivity samples. This technique can be also used with lower loss tangent resolution for measurements of low permittivity materials.

2. Whispering gallery mode dielectric resonator technique for measurements of low loss dielectrics

The most effective way to decrease radiation or conductor losses is to employ higher-order modes, called whispering gallery modes, that can be excited in spherical or cylindrical specimens (dielectric resonators) made of material under test.[4–6] For open dielectric resonators radiation losses decrease very rapidly when the order of modes and permittivity increase as it is presented in Fig. 3. One can observe that it is possible to choose mode index "n" such that radiation losses become negligible (to compare to dielectric losses in the sample) for all modes having indices $\geqslant n$.

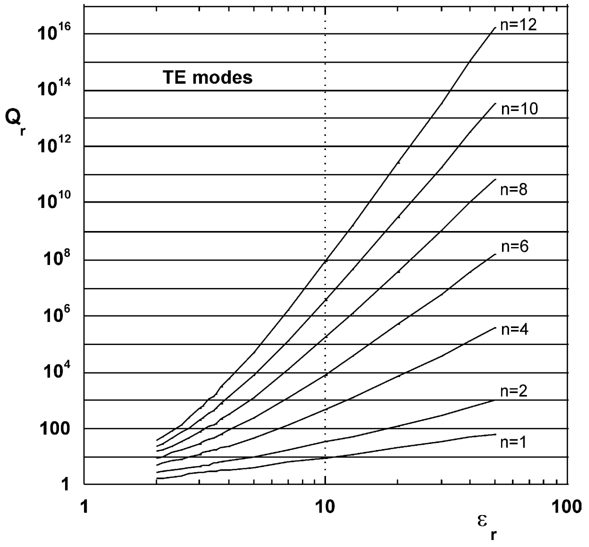

Fig. 3. Q-factors due to radiation of TE_{n01} modes versus permittivity for an open spherical resonator.

For shielded whispering gallery mode resonators parasitic losses are associated with conductors. Again conductor losses can be made arbitrarily low for all the modes having indices $\geqslant n$, if the dielectric resonator (sample) is situated at a certain distance from the metal shield. This is shown in Fig. 4 for a shielded spherical resonator. The same is true for shielded cylindrical whispering gallery mode (WGM) resonators. Using WGM technique loss tangent values as low as 10^{-10} have been measured (sapphire at liquid helium temperature). Whispering gallery mode technique has not only the highest resolution for dielectric loss tangent measurements but it is also one of the most accurate techniques for permittivity determination providing that the modes are identified properly. WGM technique can be employed for a very broad frequency range from few GHz up to few hundred GHz but it is difficult to use and applicable only for measurements of very low loss materials.

3. Measurements of laminar materials using split post dielectric resonator technique

Split post dielectric resonators (SPDRs), shown in Figs. 5 and 6, are used for non-destructive measurements of laminar or tape dielectric materials.[7–11]

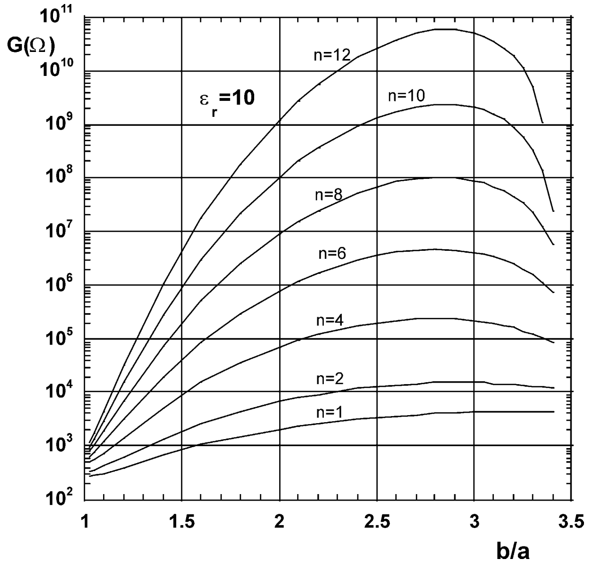

Fig. 4. Geometric factors of TE_{n01} modes versus normalized radius of a perfect conducting shield for spherical resonators with permittivity $\varepsilon_r = 10$ (**b** is radius of the metal shield, and "**a**" is radius of a spherical resonator).

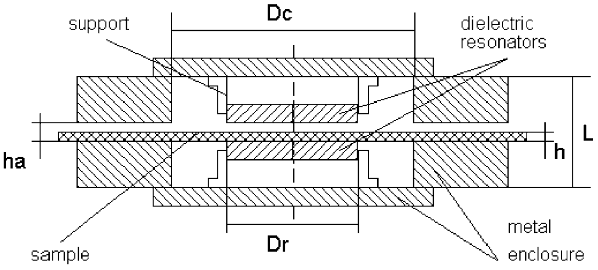

Fig. 5. Cross-section of a split post dielectric resonator.

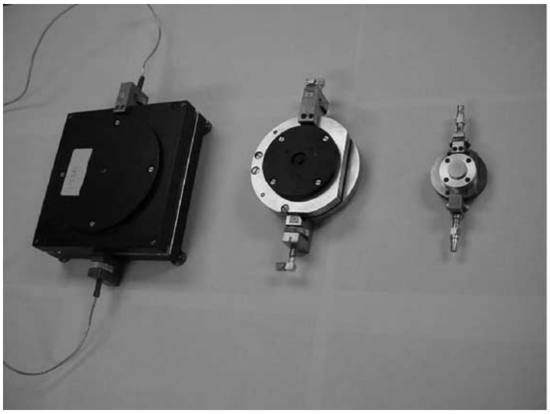

Fig. 6. Photograph of split post dielectric resonators operating at frequencies: 1.4, 3.2 and 33 GHz.

It was shown previously[10] that this technique permits measurements of permittivity with accuracy 0.3% and dielectric loss tangent with resolution down to 2×10^{-5}. Range of operational frequencies for split post dielectric resonators have been currently extended up to 33 GHz.

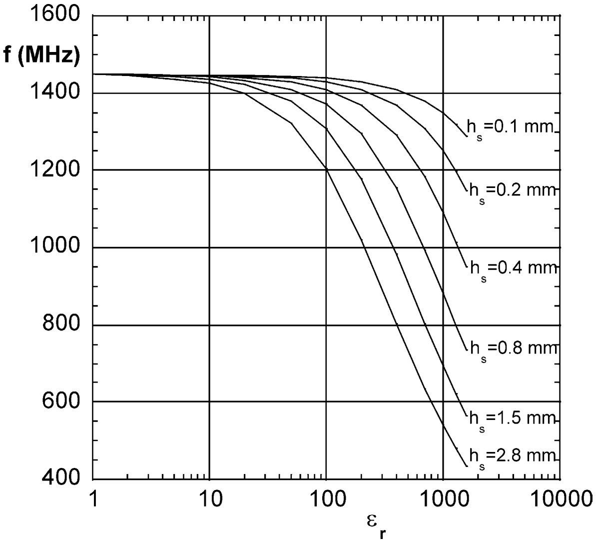

Fig. 7. Resonant frequency of 1.45 GHz split post dielectric resonator versus permittivity and thickness of samples. SPDR have been designed for measurements of ferroelectrics.

One of the main advantages of split post dielectric resonators compared to split cavities is that they can be optimized for measurements of specific materials (e.g. ferroelectrics) by appropriate design (especially by appropriate choice of permittivity and dimensions of the dielectric resonators). Recently split post dielectric resonators have been manufactured for measurements of materials having permittivities larger then 1000. As is seen in Fig. 7 it is possible to measure relatively thick samples ($h<0.3$ mm) having permittivities > 1000 with resonant frequency shifts not exceeding 20%.

4. Conclusions

Recent developments of resonant techniques made it possible to measure dielectric materials having arbitrary low dielectric losses at frequencies up to 50 MHz. Low to medium loss isotropic materials can be characterized employing $TE_{01\delta}$ mode dielectric resonator method and the lowest loss materials both isotropic and uniaxially anisotropic can be measured using whipering gallery modes technique.

A range of operational frequencies for split post dielectric resonators have been extended up to 33 GHz. Split post dielectric resonators can be used to measure the complex permittivity of laminar dielectric materials having broad range of permiitivities and dielectric losses.

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