Quick reference—Part I

TM923 Triple frequency dielectric measurement system—sample permittivity ε' up to 7 and loss factor ε'' up to 0,015.

Specifications

Frequency ranges	Dielectric properties at about 0,95 and 2,26 GHz. Assessment of magnetic properties at about 2, 44 GHz.
Sample dimensions	Diameter (10,0±0,1) mm; length >34 mm. The insertion end must be blunt (sharp circular).
Sample	*System as such*: Complex permittivity ε'–jε'' up to about 12–j5. *This sheet is for*: ε'–j$\varepsilon'' \leq$ 7–j0,015. [The loss tangent tanδ is $\varepsilon''/\varepsilon'$.] A Quick Reference part II is available, for evaluation of samples up to the highest measurable ε' and ε'' data.
Temperature	–20 °C to +100 °C.

Microwave instrument requirements and settings

The resonant peaks are narrow for low-loss materials. The frequency resolution setting of the swept frequency source should therefore be 10 kHz. This may necessitate different instrument calibrations for the two frequency ranges.

The dB sensitivity should be 0,01 dB or better.

Measurements are made in only transmission amplitude mode ($|S_{21}|$), with resonant frequency and cavity transmission (in dB) as results.

Accuracy and resolution

The resolution in ε' is about 5 MHz/unit for both frequencies, i.e. 10 kHz corresponds to 0,002 units. The obtained ε' is independent of ε'' and is accurate to better than 0,004 for a properly calibrated system.

The resolution in ε'' is about 5 times higher in the 0,9 GHz than the 2,3 GHz range†. As an example, for ε'=3 at the low frequency (and typical cavity wall conductivity and feed), a transmission difference of 0,1 dB corresponds to a ε'' difference of about $3{\cdot}10^{-4}$ (i.e. a tanδ difference of 0,0001). If ε' is very similar between two samples, the transmission difference becomes a very accurate variable for determination of their ε'' difference.

The ε'' formulas are accurate to 0,02 dB or better for both bands. This includes two sources of error: *a)* the cavity field changes with ε' of a lossless sample and results in a change of the Q value and transmission at resonance; *b)* the inaccuracy of the equation for obtaining ε'' from measured differences in Q value or transmission at resonance. For example, the transmission is 0,32 dB less with a sample having ε =4–j0 than in empty condition, at the high frequency; for the low frequency it is about 0,03 dB less. Therefore, ε'' values become more reliable for high-ε' samples at the low frequency – but ε'' comparisons for samples with high but very similar ε' will become accurate at the high frequency as well.

The sample diameter influences the measurements, which are basically by volume. A 0,1 mm diameter error gives an error in (ε'–1) and ε'' of about 2 %.

Best practice

The inside of the cavity must be kept clean. Pure (99 %) ethanol is recommended, followed by an empty cavity measurement after drying. Note that a trapped object may be difficult to remove. Disassembly of the cavity is a last resort. All screws must then be equally tightened.

The most common problem is with the cables and contacts, particularly between the generator and the cavity input. The cavity is typically very mismatched. Therefore: check the cables and contacts with a short and open before connecting the cavity.

The system should always be calibrated with the empty cavity before, during and after the run of measurements. Note that all measurements are of the differences with and without sample. If the empty cavity data are not the same as before, suspect a cable/contact error or a contaminated cavity.

Measurement procedure

1. If the sample temperature is of importance, equalise the cavity and samples in a dry environment at the desired temperature. Measure and note this.

† This is a consequence of the cavity design with about equal sensitivity for ε' and the cavity feed design giving about the same coupling factors for lossless samples; the dynamic range of the system is maximised by these choices.

2. Calibrate the instrument for $|S_{21}|$, using proper resolutions in each frequency band.
3. Measure the empty cavity resonant frequency f_{R0} (MHz) and the attenuation T_{R0} (dB), at both frequencies and check that data are consistent with earlier ones.
4. Check that the sample(s) are clean and have no burrs. If not done before: check the diameters.
5. Insert the first sample and put an instrument marker at the resonance peak. Measure f_{RS} (MHz) and the attenuation T_{RS} (dB).
6. Measure the other samples, interspersed with an empty cavity measurement after about 5 samples or 3 minutes, whichever gives the shortest time.
7. Finally, measure the empty cavity again.

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Permittivity evaluation procedure

The equations below are marked *L for the 0,95 GHz band and *H for the 2,3 GHz band. Unmarked equations are general.

The equations are given for a cavity with empty transmission data of about 8 dB and 6 dB at the low and high frequencies, respectively – and empty Q values of about 1550 and 1600, respecively. 1 dB and 10 % changes of these data give no significant error.

MATLAB® files containing all equations are available.

The real permittivity ε′

1. Calculate the sample frequency shift $f_{R0} - f_{RS} = df$.
2. Insert df in equation(s) (1) to directly obtain the sample ε' value(s).

The loss factor ε″

1. Calculate the sample attenuation $T_{R0} - T_{R1} = T_S$ (dB). Note that this value is positive.
2. Insert the sample ε' in equations (2) to obtain the transmission correction(s) ΔT for the cavity with a lossless sample of the actual permittivity.
3. Insert $T_S - \Delta T = T$ in equations (3) for calculating ε''. Note that there are breaks in the **H** equations for low ε''.

Equations

Frequency differences df are in MHz and all transmission values are in dB.

The real permittivity ε′

$df = f_{R0} - f_{RS}$

$$\varepsilon' = (1{,}00229 + 0{,}154264 \cdot df)/(1 - 0{,}004933 \cdot df + 6{,}4553\text{E}{-}5 \cdot df^2) \qquad (1L)$$

$$\varepsilon' = 0{,}756196 + 0{,}2427366 \cdot df - 0{,}00342752 \cdot df^2 + 0{,}000220337 \cdot df^{-2.5} + 0{,}2438038 \cdot e^{-df} \qquad (1H)$$

The correction factor ΔT (due to field changes by a lossless sample)

Note that ΔT below is a positive number, in dB.

$$\Delta T = -0{,}00597 + 0.00637 \cdot \varepsilon'^{\,-1{,}20725} \qquad (2L)$$

$$\Delta T = -0{,}04799 + 0{,}04876 \cdot \varepsilon'^{\,-1.45646} \qquad (2H)$$

The loss factor ε″

$T = T_{R0} - T_{R1} - \Delta T$

Low frequency:

$$\varepsilon'' = 2{,}07018\text{E}{-}5 + 0{,}002322 \cdot T^{-1{,}1555} \qquad (3L)$$

Note: This equation is independent of ε'.

High frequency:

First calculate ε'' by:

$$\varepsilon'' = 0{,}01 \cdot T/(0{,}3695 + 0{,}15206 \cdot e^{\varepsilon'/3{,}7069}) \qquad (3H)$$

Note: This equation is linear in ε''/T and dependent of ε'.

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*Assessing magnetic properties**

There is a third resonance, at about 2430 MHz. This is quite insensitive to ε': the resonant frequency drops by less than 0,5 MHz with non-magnetic samples having up to $\varepsilon = 3 - j1$ or $6 - j0{,}1$.

With samples having a real permeability $\mu' > 1$, the resonant frequency drops significantly: for $\mu' = 3$ and μ'' up to 0,2 – and $\varepsilon' = 3$ to 6 – it drops by 5 MHz.

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* A manual for evaluation of combined dielectric and magnetic properties and losses in certain regions of such properties is available as an option.

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