

Measuring complex Dielectricity constant of Aluminum Oxide window ceramics for TTF-power couplers at DESY

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Abstract

Aluminum Oxide is the standard dielectric material serving as gas barrier between vacuum of accelerating cavities and transmission line gas atmosphere which allows high RF power transmission as well. For proper design of RF power couplers it is important to know the actual material dielectric behaviour given by dielectricity constant and loss tangent in order to minimize reflections and to provide for enough cooling. Those manufacturer data often are unprecise, incomplete and especially not available for low temperature applications.

In February this year N. Sobenin (Moscow State Engineering Physics Institute) et al. finished a work on this topic for DESY. This paper continues that work at DESY.[1] ...[4]

1 INTRODUCTION

The different TTF high power input couplers –the most actual one is TTF3 (see Fig.2) - are designed for 1.3 GHz pulsed power operation up to 250 kW with each pulse starting at full reflection of the unexcited cavity. More than 1 MW pulsed test and conditioning power are necessary to establish reliable operation. Average power is up to about 5 kW. TTF3 is a coaxial coupler consisting of 2 parts, one ‘cold’ part with an Al₂O₃ window at 70K temperature level closing the cavity vacuum inside the cryostat and a ‘warm’ part with an additional room temperature Al₂O₃ window integrated into the transition between the feeding WR650 waveguide and the coaxial coupler. The reason for two vacuum windows is that in case of window damage the cryostat with its superconducting cavities stays still under vacuum

For design of the couplers which are actually operated in TTF and especially for new ones it was and it is important to know precisely dielectricity constant and dielectric losses of the applied window ceramic material. Otherwise coupler mismatch and insufficient cooling may result. These dielectric data are provided by manufacturers unsystematically for some frequencies and temperatures. Normally they are not available for the actual case and especially for 70K applications there are no data available. This lack of knowledge led to a cooperation project with Moscow State Engineering Physics Institute and resulted in manufacturing several resonators for measurement of ceramic dielectricity constant and losses of the TTF3 coupler ceramics. Measurement method, results and resonator drawings were published in papers [1] .. [4] . The idea was continuation and completion of those measurements at

DESY and additionally to have standard procedures and tools for measurements at any ceramic material. It turned out that the mentioned reports are difficult to use as a working paper just to start measurements.

This paper tries to give a short overview of basic theory concerning dielectricity behaviour and formulae to use for measurements and evaluation. Finally step by step descriptions and formulae are given for direct and easy use in the lab. The specialty of this work is that relative dielectricity constant and losses are determined in a resonator not in the classical way for small samples which don't change the field distribution in the resonator too much. Quite contrary to that the aim is measurement at complete ceramic parts like coupler windows (see Fig. 3, vacuum windows of TTF3) which considerably change field distribution in the measurement resonator (see Fig. 4).

2 THEORY

- a) Definition of dielectricity constant and dielectric losses. In case of no conduction loss both form a complex number

$$\epsilon = \epsilon_0 * \epsilon_r * (1 - j * \tan \delta)$$

ϵ_0 Dielectricity factor of empty space,

ϵ_r relative Dielectricity factor of the actual sample material,

$$\tan \delta \text{ loss factor, } j = \sqrt{-1} \quad (1)$$

- b) Complex power p and energy W in a ceramic volume

Pcomplex(in a Volume Element)

$$= U_{eff} * I_{eff}^*$$

$$= 1/2 * E_{peak} * \dot{D}^* * dl * dF$$

$$= -j\omega \epsilon^* E_{peak}^2 * dV / 2$$

$$= -j * \omega * \epsilon_0 * \epsilon_r * E_{peak}^2 *$$

$$(1 + j * \tan \delta) * dV / 2$$

blind_power

$$= -j * \omega * \epsilon_0 * \epsilon_r * E_{peak}^2 / 2 * dV$$

$$= -j\omega * Wc$$

(2a)

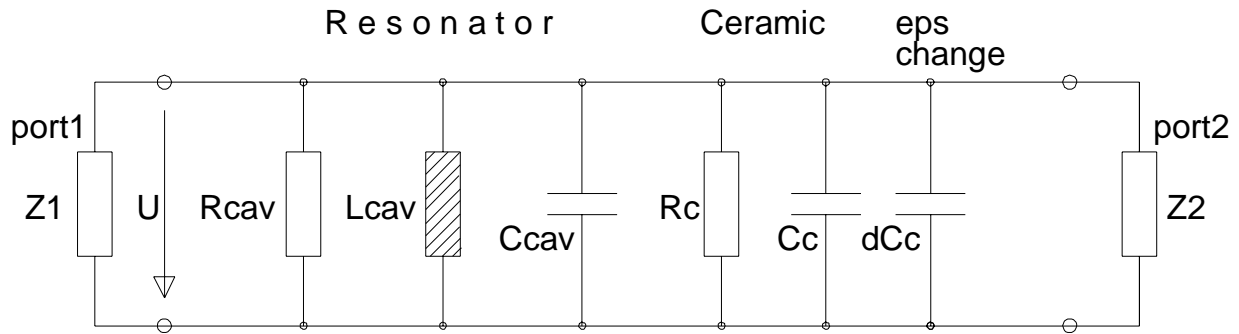


Figure1: Replacement circuit for TM010 Resonator with ceramic object in it

$$loss_power = \int \omega * \epsilon_0 * \epsilon_r * \dots$$

$$1/2 * E_{peak}^2 * \tan \delta * dV = Pc$$

f frequency, *dV/dF* volume length/cross section

U_{eff}/I_{eff} effective voltage/current across volume *dV*

E electric field strength, $\omega = 2 * \pi * f$,

Wc/Pc stored energy/loss power inside ceramic

(2b)

3 RESONATOR WITH CERAMIC SAMPLE IN IT

3.1 Determining relative dielectricity factor

The resonance type most suitable for measurements of dielectricity constant is TM010 of cylindrical cavities. This is easiest to be described by means of a simple parallel resonant circuit (see Fig. 1).

L_{cav} and *R_{cav}* describe inductance and losses of the cavity. *C_{cav}* is to describe the capacity of the cavity area outside a dielectric sample. *C_c* describes the capacity of the area for a dielectric sample with ϵ_r . This area is part of the cavity and contributes a capacity *C_c* ($\epsilon_r = 1$) also without the dielectric sample in the cavity, which means $\epsilon_r = 1$. *dC_c* is thought to symbolize an increase $\Delta\epsilon_r$ of ϵ_r in the *C_c* area. Hence we get :

$$dC_c / C_c = \Delta\epsilon_r / \epsilon_r \quad (3)$$

R_c describing the sample losses is comparable to *R_{cav}* because Al2O3 ceramics have low losses.

With *U* being the cavity peak voltage at *dC_c* = 0 in a first case and *dC_c* > 0 in a second case (change of dielectric constant in the sample area by insertion of a sample) one finds two resonant frequencies given by ω_0 and ω_1 .

generally $\omega^2 =$

$$((U^2 / 2) / L) / (C * (U^2 / 2))$$

$$\sim 1/Wc$$

(4a)

$$\rightarrow \omega_0^2 / \omega_1^2 = Wc1 / Wc0$$

$$= 1 + dC_c / (C_{cav} + C_c)$$

(4b)

The classical method of determining ϵ_r is based on only small resonator perturbations by insertion of a dielectric sample which don't change the field distribution of the resonator. This may be simulated by setting *dC_c* > 0 [fig.1]. Then one finds easily a relation yielding ϵ_r . *dC_c* in the above replacement circuit might describe insertion of a thin cylindrical rod of any small cross section parallel to the resonator electric field, it's length filling the whole length of the resonator.

$$\omega_0^2 / \omega_1^2 = (Wc0 +$$

$$dW_0 * (\epsilon_r - 1)) / Wc0$$

$$W(C_c \text{ without dielectric rod} \rightarrow \epsilon_r = 1) = dW_0,$$

$$\Delta\epsilon_r = \epsilon_r - 1 \rightarrow dC_c > 0,$$

$$W(C_c \text{ with dielectric rod} \rightarrow \epsilon_r > 1) = dW_0 * \epsilon_r,$$

$$\text{energy increase} : dW_0 * (\epsilon_r - 1)$$

(5)

Knowing total field energy of the resonator and field strength inside the sample from classical analytic computations equation (4) can be evaluated for ϵ_r . In case of samples of different shape similar procedures yield ϵ_r . Yet this is not topic of this work.

In case of big samples –like the TTF3 ceramic vacuum windows- the original TM010 field of a is heavily disturbed. One has to find their relative dielectric constant by numerical methods via modern computer programs which allow determination of fields, resonant frequencies, stored energies, Q (quality) - values .. of resonators with dielectric objects of any size and shape. The procedure simply starts by computing the resonant frequency of a given test resonator resonator (see Fig.4) without and with a dielectric

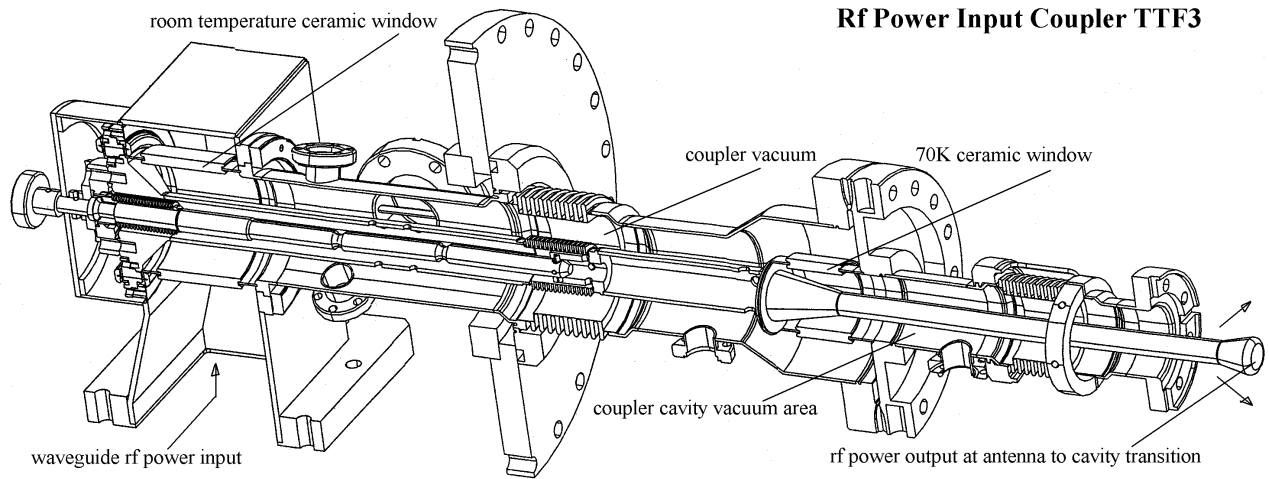


Figure 2: TTF3 power coupler with two vacuum windows, a 'warm' one placed at room temperature and a 'cold' one at 70 K level

object [fig.] of a series of different dielectricity constants, such getting a curve [fig.] of ϵ_r vs frequency. After measurement of resonant frequency with the sample one can read ϵ_r from the curve. Direct reading from the computed curve may result in a certain mistake because there are some error sources like a difference of real and computational geometry. The geometry approximation of the computer program may lead to small systematic errors. Also the shrinkage of the resonator by cooldown from room temperature to liquid nitrogen temperature will cause a slight absolute frequency shift.

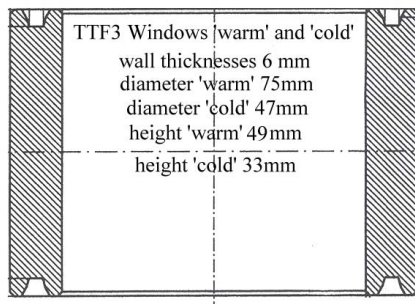


Figure 3: TTF3-Windows to be inserted as measurement samples into a test resonator

Under assumption that the relative computation error of determining resonant frequency depending on ϵ_r in all these cases is much less than the absolute error one can shift the measured resonant frequency values to the proper point of the computed curve by following equation:

$$\omega_0(\epsilon_r) = \omega_{computed}(\epsilon_r = 1) + (\omega_{measured}(\epsilon_r > 1) - \omega_{measured}(\epsilon_r = 1)) \quad (6)$$

The proper ϵ_r value can be read at position ω_0 of the computed curve $\omega_0(\epsilon_r)$.

3.2 Determining dielectric losses

Dielectric losses can be found as well by comparison of numerical and measurement results like ϵ_r above. This requires numerical computation of resonator Q-values for different loss factors at each ϵ_r value and finally evaluation of a three dimensional field. Appropriate choice of the resonator surface conductivity is presumed. In the following there are two different methods described. The first one uses the series of different resonator frequencies which are already needed for a). From this series of frequencies versus dielectric constant ϵ_r of the sample one can deduce the derivation of $\omega(\epsilon_r)$. This is used in the following method.

a) The measurable information due to losses of a dielectric sample is included in the total resonator Q-value including a lossy ceramic sample Q_{rc} . With Q_{rc} being the resonator Q-value with a lossless ceramic sample and Q_{cl} being the resonator Q due to only the ceramic sample losses (without the resonator's wall losses) we get (using (2) and the relation for resonator Q-definition and Q-addition) :

$$\begin{aligned} 1/Q_{rc} &= 1/Q_{rc} + 1/Q_{cl}, \\ 1/Q_{rc} &= Pr / (\omega_0 * W_0), \\ 1/Q_{cl} &= Pc / (\omega_0 * W_0) \\ &= W(Cc) * \tan \delta / W_0 \end{aligned}$$

W_0 total stored resonator energy(including sample),

$W(Cc)$ sample energy, Pc sample losses, $\omega_0 = 2 * \pi * f_0$,

Pr resonator wall losses, f_0 resonant frequency with sample of ϵ

(7)

Q_{rc} is known from measurement. Q_{rc} (lossless ceramic) has to be found numerically after determining the appropriate resonator surface conductivity. This is done easiest by matching the computed Q-value $Q_{rc}(\epsilon_r = 1)$ of the resonator without any dielectric sample (using for example the theoretical wall conductivity) to it's measured Q-value $Q_{rc,meas}(\epsilon_r = 1)$ without sample.

Then the computed $Q_{rc}(\epsilon_{r-ceramic})$ of the resonator with a lossless ceramic can be corrected by the factor

$$\alpha = Q_{rc,meas}(\epsilon_r = 1) / Q_{rc}(\epsilon_r = 1) \quad (7a)$$

This factor even corrects for big Q differences like operation of a copper resonator at room temperature or at 70K. The Q changes are linear with surface conductivity. In case of very small increase of the sample ϵ_r by $\Delta\epsilon_r$ (which causes $dCc > 0$) we also get a change of ω_0 by $\Delta\omega$. Then we can transform (4) by means of (3).

$$\begin{aligned} \Delta\omega, \Delta\epsilon_r &\rightarrow 0, \omega_1 = \omega_0 + \Delta\omega, \\ \omega_0^2 / \omega_1^2 &= 1 - 2 * \Delta\omega / \omega_1, \\ (Cc_{av} + Cc) / Cc & \\ = W0 / W(Cc), (\omega_1 \rightarrow \omega_0, (4)) & \\ \rightarrow -2 * \Delta\omega / \omega_0 & \\ = (\Delta\epsilon_r / \epsilon_r) / (W0 / W(Cc)) & \end{aligned} \quad (8)$$

Solving (7) for $\tan\delta$ and replacing $W0/W(Cc)$ by (8) we get a result for the ceramic sample losses.

$$\begin{aligned} \tan\delta &= (1 / Q_{rc} - 1 / (\alpha * Q_{rc})) * \\ &(\omega_0 / 2 * \epsilon_r) / (\Delta\omega / \Delta\epsilon_r) \end{aligned} \quad (9)$$

Here we need the derivation $(\Delta\omega/\Delta\epsilon_r)$ of $\omega(\epsilon_r)$ at position ω_0 . α compensates for the difference between computational and real resonator wall losses.

b) Another method of finding loss factor needs the capability of the numeric program to work also with lossy dielectric material in a resonator and to determine the resonator Q-value Q_{cl_1} which is only due to the ceramic losses of a $\tan\delta_1$ chosen near to the expected one.

$$Q_{cl_1} = W0 / (\omega_0 * W(Cc) * \tan\delta_1) \quad (10)$$

Between the real Q_{cl} (7) together with the real $\tan\delta$ and $(Q_{cl_1}, \tan\delta_1)$ there is the relation

$$Q_{cl} / Q_{cl_1} = \tan\delta_1 / \tan\delta \quad (11)$$

Together with (7) and (7a) we easily get :

$$\begin{aligned} \tan\delta &= \tan\delta_1 * Q_{cl_1} * \\ &(1 / Q_{rc} - 1 / (\alpha * Q_{rc})) \end{aligned} \quad (12)$$

α compensates for the difference between computational and real resonator wall losses also here.

4 SHORT REMARK TO THE MEASUREMENT TECHNIQUES

Clearly the Q-values, especially those which are computed, refer to an unloaded resonator which means that the port losses in Z1 and Z2 (see Fig.2) should be low or eliminated after measurement of their external Q-values which are defined by the stored energy of the resonator and the port losses comparable to (7). After scalar measurement of the scattering parameters S11, S22, S21 the external Q-values can be determined easily. For convenience the formulae are given here. Undercritical coupling of port 1 means S11 < 0. The formulae are valid for port 2 correspondingly by exchange of S11 and S22.

$$\begin{aligned} Q_{ext1} &= 2 * Q_{measured} / (S11 + 1) \\ &= 2 * Q_{measured} * (S22 + 1) / S21^2 \end{aligned} \quad (13)$$

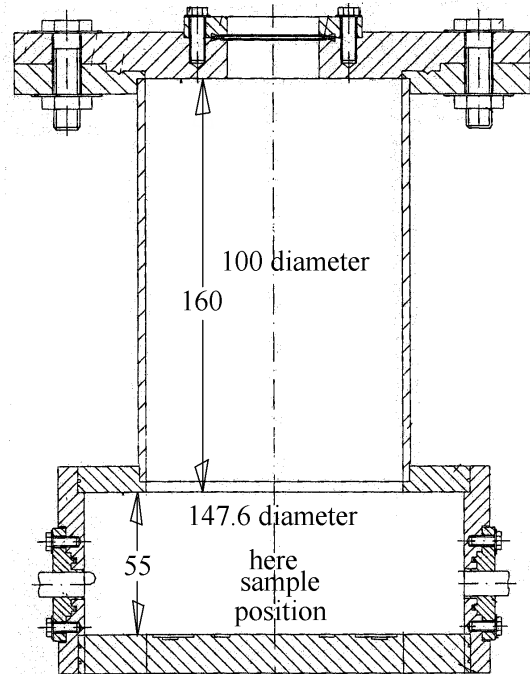


Figure 4 : Testresonator for measurement of complex dielectricity constant

5 TEST RESULTS

The above described measurement techniques were tested at DESY by remeasuring especially the 2 TTF3 ceramic windows. Two different ones were tested at 273K and 70K. One of the most interesting questions was

ceramic window type	temperature [K]	f (ε _r) / GHz	ε _r	tan δ [10 ⁻⁴]
'warm' ceramic , WESGO	300,00	1,30	9,88	2,10
'warm' ceramic , WESGO	70,00	1,30	9,81	0,46
'warm' ceramic , Friatec F99.7	300,00	1,30	9,91	4,70
'warm' ceramic , Friatec F99.8	70,00	1,30	9,85	0,60
'cold' ceramic , WESGO	300,00	1,40	9,46	4,80
'cold' ceramic , WESGO	70,00	1,40	9,45	0,44
'cold' ceramic , HIP ,yellowish	300,00	1,40	11,39	17,90
'cold' ceramic , HIP ,yellowish	70,00	1,40	11,45	4,40

Figure 5 : Measurement results for different 'warm' and 'cold' TTF3 coupler windows

whether there would be differences of dielectric behaviour between both temperature levels. The measurement results are listed in the table above (see Fig.5). It is not intended here to compare the results with those presented in references [1] ... [4]. Nevertheless : Some results are very similar. Other results differ very much. For example the dielectricity constant and the losses of the HIP-ceramic are much higher than the other ones. It seems additionally that the loss tangent is much reduced at low temperature.

The data needed for evaluation of the measurements are shown in the following diagrams (see Figures 6 and 7) :

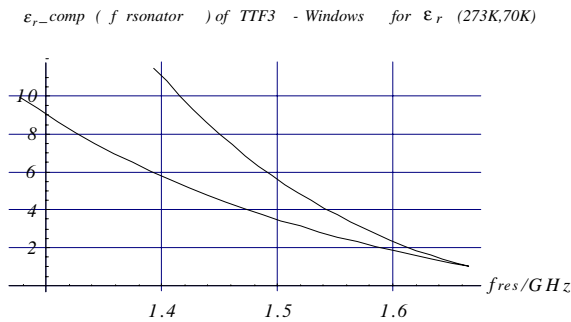


Figure 6 : Dependency of relative dielectricity and test resonator frequency

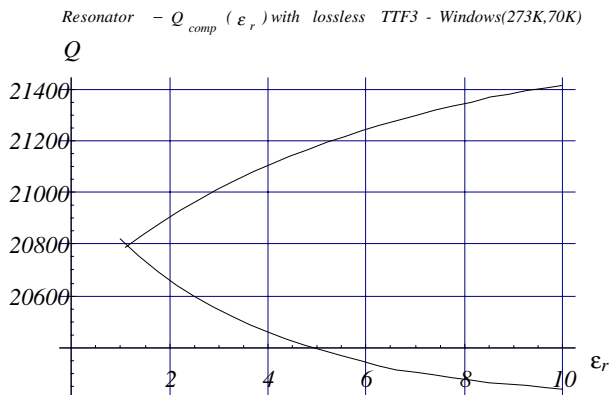


Figure 7 : Test resonator Q vs relative dielectricity of lossless windows in it.

The upper curve of figure 6 corresponds to a 'cold' type of window in the test resonator. The lower curve to the 'warm' ceramic at ε_r values between 1 and 10.

Figure 7 shows the Q-change of the test resonator which is purely due to the changing wall losses at different ε_r values. Here the upper curve corresponds to the 'cold' ceramic influence , the curve below shows the 'warm' ceramic's behaviour.

6 CONCLUSIONS

For design of high power couplers it is very important to know the complex dielectricity behaviour of the ceramic material to be taken for the rf vacuum windows. After a first step of realizing a standard measurement method to solve this problem (see references [1] ... [4]) this is a second step done at DESY. The measurement results have to be carefully studied . More measurements are necessary in order to acquire more experience.

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