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New approach for open resonator analysis for dielectric measurements at mm-wavelengths

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Abstract

Impedance transformation theory has been applied in order to describe a spherical Fabry-Perot resonator with monolithic dielectric samples at different positions along the resonator axis. The information due to different sample positioning in the resonator allows increasing accuracy in the evaluation of dielectric properties. Low loss materials like CVD-diamonds were taken as test specimens. The formalism can be extended to the case of sequences of dielectric layers. Experimental and modelling results are presented for two cases of sample geometry: resonant and anti-resonant. As an example the influence of additional surface loss on resonator parameters is quantified.
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1. Introduction

The open resonator technique is a powerful method to obtain dielectric properties of low-loss materials. One typical resonator arrangement is the symmetrical one with two spherical mirrors and a specimen positioned at the center.[1] Standard resonator theory distinguishes the symmetrical and anti-symmetrical field distribution in the resonator related with odd and even axial mode number.[2] Measurements of dielectric properties are generally provided for specimens with resonant thickness, for which one measures the resonator parameters—loaded quality factor (Q_m) and centre frequency f_m—corresponding to the centred position of the specimen and another shifted by one-quarter wavelength from the center.[3,4] Then approximate formulations for these two cases (even and odd axial mode) are used to evaluate the dielectric parameters. The measurement technique can be refined by introducing a new method based on impedance transformation (IT) theory which allows the more convenient analyses of the resonator with the specimen at arbitrary position and even of arbitrary thickness in general.

This approach was experimentally realised by setting up a symmetrical resonator consisting of two spherical glass mirrors with optical grade silver coating. Q-factor of the resonator as high as 580,000–640,000 allows the study of loss at a level of tan$\delta \approx 10^{-5}$. Chemical vapour deposition (CVD) diamond disks were positioned as test objects along the resonator axis with a motor-driven specimen holder. These specimens are typically used for high power window in fusion plasma heating.[5] The observed resonance frequency (in range of 140 GHz) and the Q-factors were measured in a set of individual positions and their apparent dielectric parameters evaluated by IT technique. It was found that the additional information obtained by means of the new approach allowed reducing uncertainties in the tanδ determination.

2. Experimental

A typical resonator as a main part of the measurement set-up is schematically shown in Fig. 1.

For our measurements a symmetric resonator with two spherical mirrors (radius of curvature $r_m = 178$ mm) was built in near-concentric geometry that provides the best concentration of the electric field in the middle of the resonator.[1,2] The resonator is coupled with outer electronics by means of two PTFE films: one for input and another for output. The thickness of the coupling films was 5 microns (the smallest thickness commercially available for PTFE). Resonator length L_{res} was about 335 mm, distance between coupling films was 114

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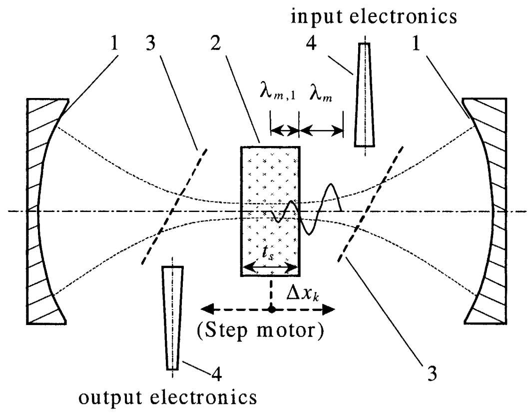

Fig. 1. Scheme of the loaded open resonator for dielectric properties measurements. 1, glass mirrors with optical grade silver coating; 2, specimen; 3, PTFE films (5 μm thick); 4, microwave horns; Δx_k, step of the motor; $\lambda_{m,1}$ and λ_m, wavelength in sample and air subsequently.

mm to allow measurements of brazed CVD-diamond structures. Q-factor for the empty resonator with the mentioned structure ranged between $Q_0 \approx 580{,}000$ and 640,000 depending on many factors such as mode number, exact resonator length, laboratory atmosphere (humidity) etc. This difference in Q-factor does not affect the resulting dielectric properties. Q_0 in IT model depends on resistance of the resonator mirrors R_S. For each measurement R_S is adjusted according to the actual Q_0. Bandwidth of the mm-wave source ranged between $f_q = 138\ldots140.6$ GHz.

In the loaded resonator a specimen is put into the centre. The motor-driven specimen holder is controlled with a computer. CVD-diamond disks with thickness of 1.7...2.14 mm were taken as test objects. A step sequence from 10 μm up to 50 μm was chosen for the experiment as a compromise between time of measurement (thus minimizes thermal and frequency drifts) and density of the data set. Primary positioning of the sample is provided in manual regime with help of a joystick and then measurements are run automatically.

The output information that is stored in the computer in the case of loaded resonator includes position of the sample, Q_m-factor, transmitted power P_m, centre frequency of corresponding mode f_m, bandwidth Δf_m. For the empty resonator the measured values are Q_0-factors, transmitted power P_0, centre frequencies of eigen modes $f_{0,i}$ and bandwidth $\Delta f_{0,i}$.

Three types of CVD-diamond disks were under investigation.

1. "49DB1" disk of resonant thickness. This means that thickness of this sample is an integer number N_λ of half wavelength of the sample medium ($N_\lambda = 4$ for "49DB1")

$$N_\lambda = \frac{2t_S}{\lambda_{m,1}}, \tag{1}$$

2. "15DB1" disk of nearly "anti-resonant" thickness: N_λ—half of integer, i.e. 3.5. Both samples had no additional surface loss.
3. "22DB4" disk of resonant thickness ($N_\lambda = 4$) that has additional surface loss.

3. Results and discussion

The results of all measurements and simulations are presented as functions of the actual axial position (x) of the sample relative to the centre of the resonator. Position is given in units of wave length (x/λ_m).

Equations of the loaded resonator for all individual points represent IT of mirror impedance Z_S from one mirror to another through air and dielectric medium. The imaginary part of the mirror impedance introduces only an insignificant change in resonator length, so impedance was replaced by the surface resistance $Z_S \approx R_S$. Equivalent scheme of such a resonator for a single position of the sample is given in Fig. 2.

For example, according to IT theory, the impedance of the "left" mirror will have the following value in reference line 1:

$$Z_1 = Z_0 \frac{R_S + i \cdot Z_0 \tan(k_1 \cdot b_1 - \Phi_{b,1})}{Z_0 + i \cdot R_S \tan(k_1 \cdot b_1 - \Phi_{b,1})} \tag{2}$$

where k_1, propagation coefficient of the medium (air); $\Phi_{b,1}$, phase coefficient.[2,6]

Then one can find the contribution of the right mirror resistance to the impedance in reference line 1 having in mind that there are two media with different properties (air and sample) between. Finally we get a system of equations that describes the resonator as a whole by joining together medium and mirror parameters. Phases for equations are taken from electromagnetic solution of the dielectric loaded open-resonator by means of complex-source-point theory.[2,6]

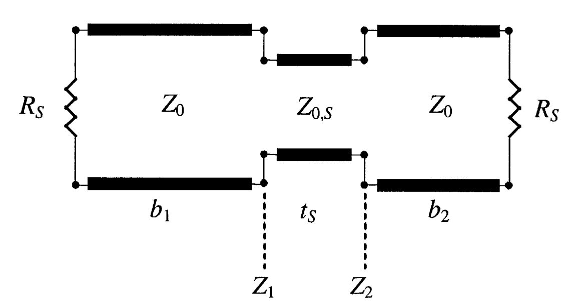

Fig. 2. Equivalent impedance transformation scheme of the loaded resonator. Where b_1, b_2 are distances between resonator mirrors and sample; t_s is thickness of the sample, Z_0, $Z_{0,S}$ are wave impedances of the medium: air and substrate; R_S is surface resistance of the mirrors. Z_1 and Z_2 are impedances in reference lines 1 and 2 consequently.

3.1. Sample "49DB1"

To provide measurements for a resonant sample it is necessary to find a corresponding "resonant" frequency [$f_{m,1} = c/\lambda_{m,1}$, see Eq. (1)] by tuning resonator length. An indicator for this condition is that the centre frequency is not changed while the specimen is being moved along the resonator axis near the center.[2,3] For "49DB1" resonant frequency was $f_{m,1} = 140.272$ GHz. After centring the sample and tuning the resonator as mentioned above measurements are controlled automatically. The length of the single motor-step was $\Delta x_k = 50$ microns.

The Q-factor (Q_m) of loaded resonant with a low loss sample without surface loss as a function of position x differs very slightly from a sinus-function. Such a behaviour can be seen in Fig. 3 where measurement and modelling results are presented.

Measured Q-factor from resonance line fitting and Q-factor from peak power transmission (P_m) are identical for almost all points except for Q_m "maximums" where $x = 0.25\lambda_m$, $0.5\lambda_m$, $0.75\lambda_m$ etc. Near these positions Q-factor from line fitting had the highest uncertainty compared with peak power which gave always stable results. This fact was used for evaluation of loss in the sample. Results of data evaluations for tanδ corresponding to Q-factor corrected by means of peak power measurements are given in Fig. 4.

Computed values of tanδ range between (1.9…2.17) 10^{-5}. Uncertainty of evaluation is about 6%.

3.2. Sample "15DB1"

Diamond disk "15DB1" has anti-resonant thickness ($t_S = 1.61$ mm, $N_\lambda = 3.5$). In this case the Q-factor (Q_m) of the modes is practically constant, but centre frequencies (f_m) of the modes are changed dramatically while sample is being moved along resonator axis. For such measurements three modes were under investigation. The frequency dependence of all three modes is presented in Fig. 5. The Q-factor dependence is given in Fig. 6 for the first mode.

The accuracy of Q-factor measurements has different values depending on position of the sample or boundary condition on the surface of the sample to be exact. This uncertainty has a periodic nature. Distance (period) between two measurements with high precision is equal to quarter of wavelength in the resonator ($\lambda_m/4$). Result of evaluation is presented in Table 1.

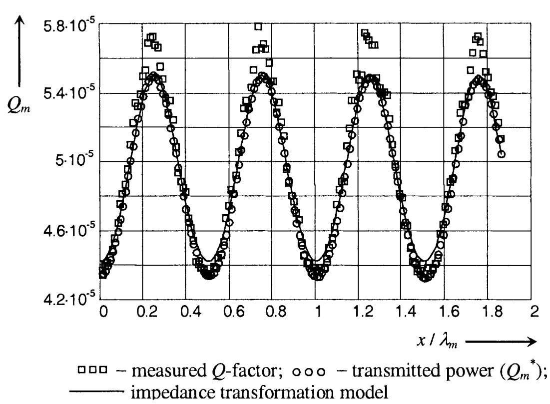

Fig. 3. Measurements and IT modelling for "49DB1" ($t_S = 1.79$ mm, $N_\lambda = 4$).

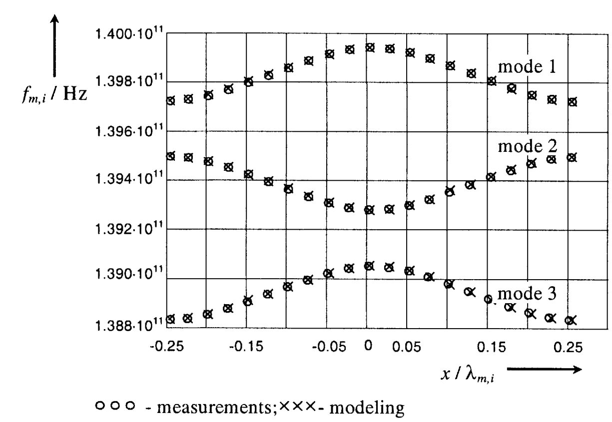

Fig. 5. Measurement and IT modelling results of frequency f_m in anti-resonant case, given for three modes.

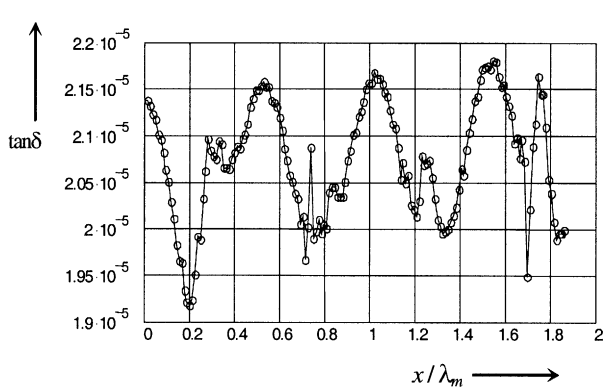

Fig. 4. Loss tangent (tanδ) of the diamond "49DB1" via position in the resonator.

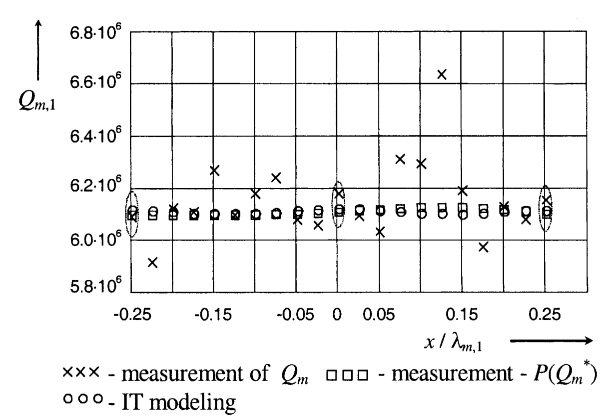

Fig. 6. Measurement and IT modelling results of Q-factor of the first mode.

3.3. Sample "22DB4"

Resonant specimen "22DB4" was measured twice following the same procedure as for resonant sample "49DB1" (see earlier). The first time after cold NaOH cleaning, and second time after hot H_2SO_4+ $NaNO_3$ cleaning. Principle difference between these cases is that after the first cold cleaning there were surface losses left, but after second cleaning all surface losses were removed. Additional surface losses modify Q-factor as shown in Fig. 7. Additional surface losses change dielectric parameters of the layer between sample and air. Therefore wave impedance of this layer (film) differs from wave impedance of the substrate, although dielectric permittivity can be assumed to be the same. IT model for resonator loaded with specimen like "film-substrate-film" become more complex as shown in Fig. 8.

Result of impedance transformation modelling for Q_m for both cases is shown in Fig. 7. Indeed, IT-model of loaded resonator for the second case corresponds to the model described in the beginning of this section and shown in Fig. 2. Unfortunately we have no direct information about the film (surface layer with additional dielectric losses) thickness t_f. This means that for surface loss characterization one can find exactly only the product term of $t_f \tan\delta_f$, where $\tan\delta_f$ - dielectric losses of the film. Dielectric parameters of "22DB4" are the following: substrate $t_S = 1.8$ mm, $\tan\delta_S = 4\times10^{-5}$; film $t_f \tan\delta_f = 2.4\times10^{-8}$. Uncertainty of evaluation was about 5%.

Table 1

Measurement points, $\frac{\Delta x}{\lambda_m/4}$	Loss tangent, $\tan\delta 10^5$		
	Mode 1	Mode 2	Mode 3
−1	0.67	0.69	0.70
0	0.66	0.67	0.71
1	0.68	0.68	0.72

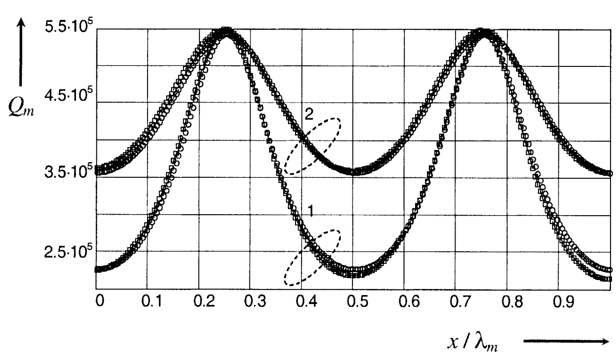

Fig. 7. (1) Measurement and model results for sample with additional surface loss (after cold NaOH cleaning). (2) Measurement and model results for sample without surface loss (after hot H_2SO_4+ $NaNO_3$ cleaning). Length of the motor-step is 10 microns.

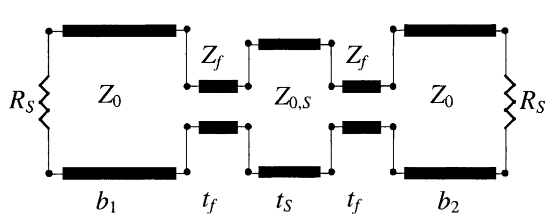

Fig. 8. Equivalent scheme of the complex dielectric structure. Where t_f is thickness of the film; Z_f is wave impedance of the film.

4. Conclusion

A refined approach in the measurement technique combined with impedance transformation theory was used in order to describe experimentally and analytically (modelling) the loaded Fabry-Perot open resonator with samples of different thickness. It was found that the additional information obtained by means of the new approach allowed reduction in uncertainties in the $\tan\delta$ determination down to 5%.

By means of impedance transformation theory it is possible to specify dielectric properties of the complex structures like film-substrate-film. For very thin films ($t_f << \lambda_m$) of unknown thickness it is still possible to find a parameter which characterises surface loss: $t_f \tan\delta_f$, where t_f is the thickness of the film.

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