NEW TECHNIQUE OF DIELECTRIC CHARACTERIZATION OF LIQUIDS

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Abstract. Quasi-optical dielectric resonators (QDR) with conducting endplates (CEP) are proposed and justified for measurement of complex permittivity of liquids. The structure of electromagnetic fields in the form of whispering gallery (WG) modes is calculated accurately in terms of Maxwell equations which allow one to characterize liquids from the first principles. A radially two-layered QDR has been shown to be rather convenient for microwave characterization of liquids including ones with large microwave loss. For experimental studies of a number of liquids in K_a-band, the QDR in the form of a Teflon disk sandwiched between the duralumin CEP was used. Here, water has shown an unusual property. The sign of the frequency shift indicates that properties of the resonator with water layer adjacent to the solid state dielectric become nearly the same as with metal layer. The proposed measurement technique can be used also for studies of nonlinear properties of liquids.

1. Introduction

The microwave technique of liquid media dielectric characterization does not differ in the main from the technique for characterization of solids [1,2]. However, the application of a traditional technique in case of liquids becomes often much more difficult because of evident inability of liquid substances to keep their own forms in space. The technique of microwave characterization of condensed matter allows one to determine complex permittivity $\varepsilon = \varepsilon' - i\varepsilon''$ of the substances. Here, the resonator approach, i.e. the most sensitive one when applied to liquids with a large loss tangent, $\tan\delta = \varepsilon''/\varepsilon'$, comes across serious difficulties conditioned by an abrupt decrease of quality factor Q of the resonant structures with such liquids.

The problems of electrodynamics analysis arising therewith do not allow one to determine ε directly. The latter may turn out to be an important problem in studies of permittivity in both weak and strong electromagnetic fields because it decreases accuracy and reliability of the analysis of experimental and theoretical results at their comparison and/or fitting. In present work, the results of the development of a new approach to liquids permittivity characterization in the microwave range are given on

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the basis of quasi-optical dielectric resonator (QDR) which are named else as dielectric resonators with whispering gallery modes (WGR) (see for example [3]).

2. The resonator with conducting endplates

The interest to QDR is caused by the potential for their use in microwave technique [4], in particular for the microwave characterization of dielectrics [5, 6] and conductors, including the studies of superconductors surface resistance [7]. However, the rigorous electrodynamic analysis of the open QDR is unavailable that presents some problems in using them for measurement purposes. A consistent analysis of the field distribution in QDR with conducting endplates (CEP) makes it possible to calculate its resonance frequencies and quality factors depending on both disk dielectric and endplate conductor properties and also dimensions of dielectric disk sandwiched between CEP [8]. In fact, QDR with CEP is a quasi-optical analogue of Hakki-Coleman resonator [9], in a classic version of which the lower modes are excited.

In practice, the WG modes are not easy to use due to increase of the resonant frequency spectrum density at higher frequencies and difficulties of mode identification. However for the millimeter wave range, QDR is the ultimate choice due to its moderate dimensions at high frequencies and much higher *Q*-factors as compared with the other types. Experimental and theoretical studies of resonant frequency evolution of QDR with CEP under variation of endplate diameter have enabled to solve a problem of the wave identification [10].

In works [8, 10] the spectral characteristics of QDR with perfect CEP were studied. The cylindrical resonator (Figure 1) was made of one-axial crystal, the anisotropic axis of which coincides with resonator longitudinal axis and was characterized by tensor of permittivity $[\varepsilon_{ij}]$ with non-zero components ε_z and $\varepsilon_\perp$ in parallel and perpendicular directions were obtained from the dispersion equation [8, 10]:

$$a_H a_E = a, \qquad (1)$$

here $a_H = X_H - X$, $a_E = \varepsilon_z X_E - X$; $a = \left[\dfrac{k_0 k_z n}{q_0^2 q_H^2 r_0^2}(1-\varepsilon_\perp)\right]^2$;

$k_0 = (\omega' - i\omega'')/c$; ω' and ω'' are the real and imaginary parts of resonant frequency ($\omega' \geq 0$); c is the velocity of light; $X_j = \dfrac{1}{q_j r_0}\dfrac{J_n'(q_j r_0)}{J_n(q_j r_0)}$;

$X = \dfrac{1}{q_0 r_0}\dfrac{H_n^{(1)'}(q_0 r_0)}{H_n^{(1)}(q_0 r_0)}$; the prime denotes differentiation with respect to argument.

Index j stands for H and E; $J_n(x)$ and $H_n^{(1)}(x)$ are the n-th order Bessel and Hankel cylindrical functions of the first kind; n=0,1,2,..., $k_z = m\pi / l$ (where l is the resonator height, $m = 0; 1; 2\ldots$), $q_H = \sqrt{\varepsilon_\perp k_0^2 - k_z^2}$, $q_E = q_H\sqrt{\varepsilon_z / \varepsilon_\perp}$ and

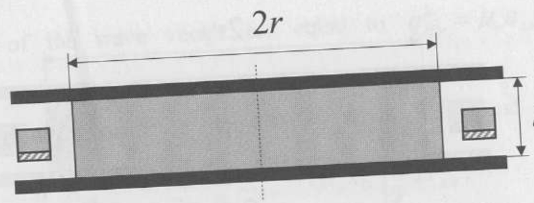

Figure 1. Cylindrical quasi-optical dielectric resonator with conducting endplates.

$q_0 = \sqrt{k_0^2 - k_z^2}$ are accordingly the azimuthal, axial and radial components of the wave vector inside and outside the resonator.

Axial components of the resonant electromagnetic fields take the form

$$E_z = D_n G_E(r)\cos(k_z z)e^{i(n\varphi - \omega t)};$$
$$H_z = C_n G_H(r)\sin(k_z z)e^{i(n\varphi - \omega t)}, \qquad (2)$$

where $G_j = \begin{cases} J_n(q_j r), & r \leq r_0 \\ \dfrac{J_n(q_j r_0)}{H_n^{(1)}(q_0 r_0)}H_n^{(1)}(q_0 r), & r \geq r_0 \end{cases}$, C_n and D_n are the constants related to each other by $a_H J_n(q_H r_o)C_n = -\sqrt{a}J_n(q_E r_o)D_n$.

Independent *EH*- and *HE*-modes can take place in the resonator. In the case of validity of condition $\left|\sqrt{a_H / a_E}\right| >> 1$ eigen oscillations have a nature of *HE*-mode, otherwise they have a nature of *EH*-mode.

Transversal components of the field are expressed in terms of axial components (2) as

$$q^2 E_\varphi = \frac{1}{r}\frac{\partial}{\partial\varphi}\frac{\partial}{\partial z}E_z - ik_0\frac{\partial}{\partial r}H_z; \quad q^2 E_r = \frac{\partial}{\partial r}\frac{\partial}{\partial z}E_z + i\frac{k_0}{r}\frac{\partial}{\partial\varphi}H_z \qquad (3)$$

$$q^2 H_\varphi = ik_0\varepsilon_\perp\frac{\partial}{\partial r}E_z + \frac{1}{r}\frac{\partial}{\partial\varphi}\frac{\partial}{\partial z}H_z; \quad q^2 H_r = \frac{\partial}{\partial r}\frac{\partial}{\partial z}H_z - i\frac{k_0\varepsilon_\perp}{r}\frac{\partial}{\partial\varphi}E_z$$

where $q^2 = \begin{cases} q_H^2, & r \leq r_0 \\ q_0^2, & r \geq r_0 \end{cases}$.

3. Two-layered (along radius) QDR with CEP

Consider two-layered (along radius) QDR with CEP in which the layers are made of different one-axial single crystals with axes of anisotropy directed in parallel with the resonator longitudinal axis (Figure 2).

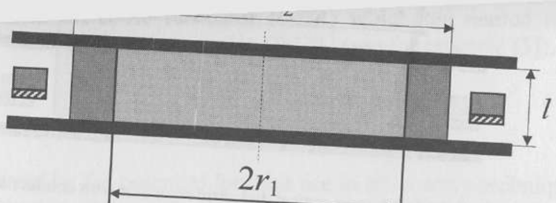

Figure 2. Two-layered quasi-optical dielectric resonator with conducting endplates.

In this case tensors of dielectric and magnetic permittivity are as follows

$$[\varepsilon_{ij}]=\begin{cases}\begin{pmatrix}\varepsilon_{\perp\nu} & 0 & 0\\ 0 & \varepsilon_{\perp\nu} & 0\\ 0 & 0 & \varepsilon_{z\nu}\end{pmatrix}, & \nu=1, \quad r\le r_1\\ & \nu=2,\ r_1<r\le r_2,\\ \delta_{ij}, & \nu=3, \quad r>r_2\end{cases}$$

$$\mu_\nu=\begin{cases}\mu_1, & \nu=1, \quad r\le r_1\\ \mu_2, & \nu=2,\ r_1<r\le r_2,\\ 1, & \nu=3, \quad r>r_2\end{cases}$$

where $\varepsilon_{z\nu}$ and $\varepsilon_{\perp\nu}$ are the components of the tensor $[\varepsilon_{ij}]$ for a ν-layer in directions which are parallel and perpendicular with regard to the crystal optical axis; r_1 and r_2 are the resonator layer radii; δ_{ij} is Kronecker symbol.

The axial components of mode electromagnetic fields of two-layered QDR mode can be expressed by the following

$$E_{z\nu}=G_{E\nu}(r)\cos(k_z z)e^{i(n\varphi-\omega t)};$$

$$H_{z\nu}=G_{H\nu}(r)\sin(k_z z)e^{i(n\varphi-\omega t)},$$

where $G_{j\nu}=\begin{cases}A_{jn}J_n(q_{j1}r), & r\le r_1\\ B_{jn}J_n(q_{j2}r)+C_{jn}N_n(q_{j2}r), & r_1\le r\le r_2\\ D_{jn}H_n^{(1)}(q_0 r), & r\ge r_2\end{cases}$ characterizes the field distribution along the radius in resonators ν-layer. Here $A_{jn}, B_{jn}, C_{jn}, D_{jn}$ are the constants determined by the boundary and mode excitation conditions in QDR; $N_n(x)$ is the cylindrical Neiman function. Inside the dielectric layers, the field radial components $q_{j\nu}$ of the wave vector are equal to $q_{H\nu}^2=\mu_\nu\varepsilon_{\perp\nu}k_0^2-k_z^2$ and $q_{E\nu}^2=q_{H\nu}^2\varepsilon_{z\nu}/\varepsilon_{\perp\nu}$:

The field transversal components are expressed in terms of $E_{z\nu}$ and $H_{z\nu}$:

$$q^2E_{\varphi\nu}=\frac{1}{r}\frac{\partial}{\partial\varphi}\frac{\partial}{\partial z}E_{z\nu}-i\mu_\nu k_0\frac{\partial}{\partial r}H_{z\nu};$$

$$q^2E_{r\nu}=\frac{\partial}{\partial r}\frac{\partial}{\partial z}E_{z\nu}+i\mu_\nu\frac{k_0}{r}\frac{\partial}{\partial\varphi}H_{z\nu};$$

$$q^2H_{\varphi\nu}=i\varepsilon_{\perp\nu}k_0\frac{\partial}{\partial r}E_{z\nu}+\frac{1}{r}\frac{\partial}{\partial\varphi}\frac{\partial}{\partial z}H_{z\nu};$$

$$q^2H_{r\nu}=\frac{\partial}{\partial r}\frac{\partial}{\partial z}H_{z\nu}-i\varepsilon_{\perp\nu}\frac{k_0}{r}\frac{\partial}{\partial\varphi}E_{z\nu},$$

where $q^2=q_{H\nu}^2$ at $\nu=1;2$ and $q^2=q_0^2$ at $\nu=3$.

Spectral properties of anisotropic radially two-layered resonator are determined by the solutions of the following characteristic equation

$$\begin{aligned}&(\chi_0\gamma_\beta^E-\chi_0\gamma_\alpha^E)(\chi\vartheta_\alpha^H-\chi\vartheta_\beta^H)Z_J^HZ_N^H+(\chi_0^2-\gamma_\beta^E\gamma_\beta^H)(\vartheta_\alpha^E\vartheta_\alpha^H-\chi^2)Z_J^EZ_J^H+\\&+(\chi_0^2-\gamma_\alpha^E\gamma_\alpha^H)(\vartheta_\beta^E\vartheta_\beta^H-\chi^2)Z_N^EZ_N^H+(\chi\vartheta_\beta^E-\chi\vartheta_\alpha^E)(\chi_0\gamma_\alpha^H-\chi_0\gamma_\beta^H)Z_J^EZ_N^E+\\&+(\chi_0^2-\gamma_\alpha^E\gamma_\beta^H)(\chi^2-\vartheta_\beta^E\vartheta_\alpha^H)Z_N^EZ_J^H+(\chi_0^2-\gamma_\beta^E\gamma_\alpha^H)(\chi^2-\vartheta_\alpha^E\vartheta_\beta^H)Z_J^EZ_N^H=0.\end{aligned}$$

In this equation, the following designations are used: $\chi_0=nk_z(q_0^{-2}-q_{H2}^{-2})/k_0r_2^2$; $\chi=nk_z(q_{H1}^{-2}-q_{H2}^{-2})/k_0r_1^2$; $\gamma_\xi^j=\sigma_2^j\xi_{22}^j-\alpha_0$; $\vartheta_\xi^j=\sigma_2^j\xi_{21}^j-\sigma_1^j\alpha_{11}^j$, where ξ takes on values α or β: $\alpha_{p\tilde p}^j=\frac{1}{q_{jp}r_{\tilde p}}\frac{J_n'(q_{jp}r_{\tilde p})}{J_n(q_{jp}r_{\tilde p})}$, $\beta_{2\tilde p}^j=\frac{1}{q_{j2}r_{\tilde p}}\frac{N_n'(q_{j2}r_{\tilde p})}{N_n(q_{j2}r_{\tilde p})}$, where $p,\tilde p=1;2$ and prime means differentiation with respect to argument; $\sigma_\nu^j=\varepsilon_{z\nu}$ at $j=E$; $\sigma_\nu^j=\mu_\nu$ at $j=H$; $\alpha_0=\frac{1}{q_0r_2}\frac{H_n^{(1)'}(q_0r_2)}{H_n^{(1)}(q_0r_2)}$; $Z_R^j=\frac{R_n(q_{j2}r_1)}{R_n(q_{j2}r_2)}$, where R means the functions J or N.

Away from the frequency degeneration region, the independent *EH*- and *HE*-modes exist in the resonator. In the case when

$$\frac{\left|\begin{matrix}\chi^2\left(Z_J^E-Z_N^E\right)\left(\gamma_\beta^H Z_J^H-\gamma_\alpha^H Z_N^H\right)+\\ +\left(\vartheta_\alpha^E Z_J^E-\vartheta_\beta^E Z_N^E\right)\left(\gamma_\alpha^H \vartheta_\beta^H Z_N^H-\gamma_\beta^H \vartheta_\alpha^H Z_J^H\right)\end{matrix}\right|}{\left|\begin{matrix}\chi_0\left[\left(\vartheta_\alpha^H Z_J^H-\vartheta_\beta^H Z_N^H\right)\left(\vartheta_\beta^E Z_N^E-\vartheta_\alpha^E Z_J^E\right)+\chi^2\left(Z_J^H-Z_N^H\right)\left(Z_J^E-Z_N^E\right)\right]+\\ +\chi\left(\vartheta_\alpha^E-\vartheta_\beta^E\right)\left(\gamma_\alpha^H-\gamma_\beta^H\right)Z_J^E Z_N^E\end{matrix}\right|}>>1$$

the eigen *HE*-modes are excited in the resonator, otherwise *EH*-modes are established.

4. The QDR frequency as a function of hole diameter in the dielectric cylinder

In practice, when using QDR a hole in the dielectric disk, concentric on the disk longitudinal axis, is often necessary. Therefore, the elucidation of the effect of a hole upon the resonator frequencies is of interest [11]. This, in its turn, initiates the formulation of the more general problem of studying the resonator spectrum at arbitrary diameter of the hole in the dielectric disk (see Figure 2). During the spectrum investigation, the hole diameter $2r_1$ is varied from zero to the highest possible value. The exterior diameter of the dielectric cylinder is $2r_2$=77.7 mm and its height is l=7.1 mm. The interior diameter $2r_1$ is changed by means of a step-by-step removal of the dielectric Teflon material. In order to maximally reduce the plastic deformations, which are brought at fixation of the dielectric disk in the process of material removal, an appropriate fastening arrangement was made. The radius variation step is selected in such a way as to prevent "jumps" (at analysis of measurement results) between dependences for modes with different index sets nsm. The EH_{n11}- and HE_{n10}-mode frequency dependences on radial thickness r_2-r_1 are shown in Figure 3a and 3b. At r_2-r_1<4 mm the *Q*-factor decreases sharply and the measurement error increases along with it. This experimental result is consistent with the theoretical calculation one. According to this result the resonator's radiation quality is dropped to such low values that the radiation loss dominance over the dielectric and metal losses becomes obvious (Figure 4a and 4b).

One can see from Figure 3a and 3b that WG modes propagate within QDR until, as was to be expected, the inside air-dielectric boundary coincides with the inside caustic line in the resonator. In our case, the caustic line is $r_2-r_1\cong$8 mm distant from the

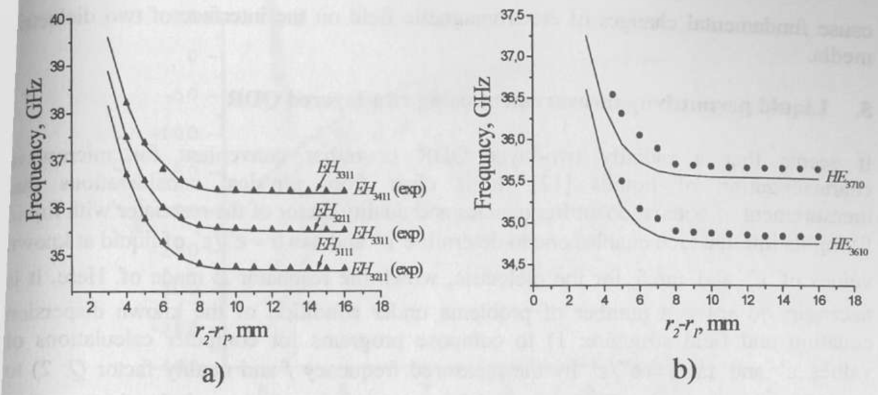

Figure 3. The EH_{n11}-mode (a) and HE_{n10}-mode (b) frequency dependences on radial thickness $r_2 - r_1$. The lines represent the results of calculations.

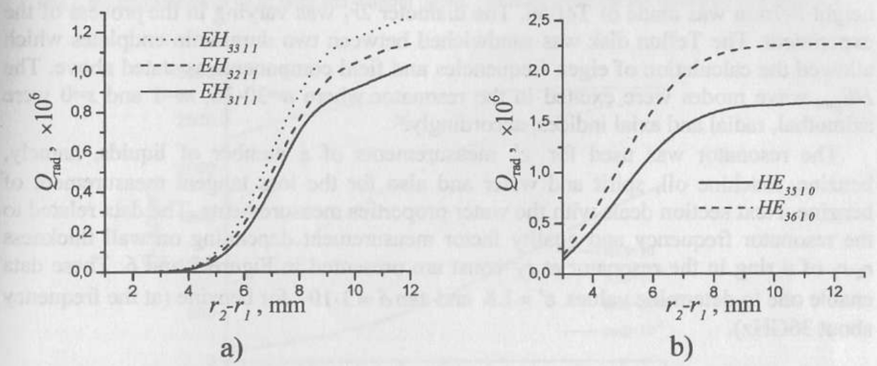

Figure 4. The EH_{n11}-mode (a) and HE_{n10}-mode (b) radiation quality-factor dependences on radial thickness $r_2 - r_1$ obtained theoretically.

dielectric cylinder periphery. At $r_2 - r_1 > 8$ mm, the ring resonator eigen frequencies are nearly independent of a hole diameter $2r_1$, while at $r_2 - r_1 < 8$ mm the frequencies increase when diameter $2r_1$ grows. The obtained experimental and theoretical results indicate an evolution nature of a whispering gallery wave transformation into waveguide modes at the continuous transition of QDR without a hole to the ring QDR (with a hole).

It is obvious, that the studied peculiarity of the QDR with CEP should also take place in the resonator without CEP because the presence of impedance walls does not cause fundamental changes of electromagnetic field on the interface of two dielectric media.

5. Liquid permittivity measurement using two-layered QDR

It seems that a radially two-layer QDR is rather convenient for microwave characterization of liquids [12]. It is clear from physical considerations that measurement of both resonant frequencies and quality factor of the resonator with liquid filling its internal area enables one to determine ε' and $\tan\delta = \varepsilon''/\varepsilon'$ of liquid at known values of ε'_d and $\tan\delta_d$ for the dielectric, which the resonator is made of. Here, it is necessary to solve a number of problems under condition of the known dispersion equation and field structure: 1) to compose programs for computer calculations of values ε' and $\tan\delta = \varepsilon''/\varepsilon'$ by the measured frequency f and quality factor Q; 2) to identify wave modes (oscillations) used for measurements; 3) to optimize the resonator dimensions from the point of view of measurement sensitivity increase. The latter is especially important at properties measurements of liquids with a large loss tangent.

For experimental measurements the resonator with diameter $D = 2r_2$=78mm and height l=7mm was made of Teflon. The diameter $2r_1$ was varying in the process of the experiment. The Teflon disk was sandwiched between two duralumin endplates which allowed the calculation of eigen frequencies and field components as stated above. The HE_{nms} wave modes were excited in the resonator where n=30-36, m=1 and s=0 were azimuthal, radial and axial indices, accordingly.

The resonator was used for ε' measurements of a number of liquids, namely, benzine, machine oil, spirit and water and also for the loss tangent measurement of benzine. Next section deals with the water properties measurements. The data related to the resonator frequency and quality factor measurement depending on wall thickness r_2-r_1 of a ring in the resonator at r_2=const are presented in Figure 5 and 6. These data enable one to determine values $\varepsilon' = 1.8$ and $\tan\delta = 3\cdot10^{-3}$ for benzine (at the frequency about 36GHz).

6. About sign of frequency shift of the resonator with water

The opened opportunity seems to be attractive for studying liquids with large microwave loss such as water, because in the resonators studied we can control the weight coefficient of liquid loss in the resonator total losses by means of changing the radius r_1 (see Figure 2). Research into the frequency properties of QDR with water shows that water in a surface layer adjacent to solid-state dielectric causes the same sign of frequency shift as metal [13]. This effect seemed unusual in comparison with that of filling QDR with other dielectric liquids. The same QDR as in section 5 is used for experimental studies. In order to rule out the possibility of measurement errors

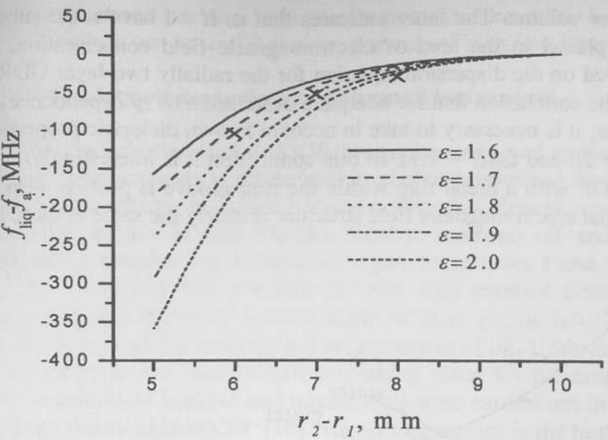

Figure 5. The shift frequency dependences on radial thickness $r_2 - r_1$ for the QDR with benzine, f_{liq} and f_a are frequencies of QDR with and without liquid. The lines represent the results of calculations.

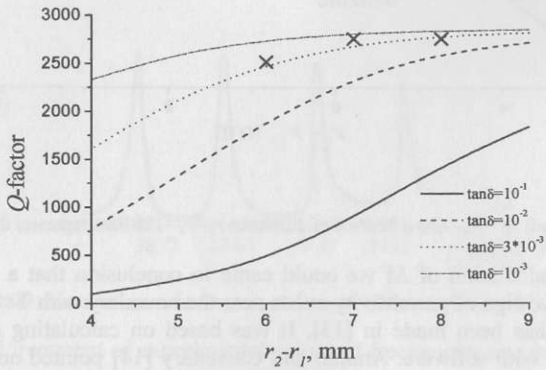

Figure 6. The *Q*-factor dependences on radial thickness r_2-r_1 for the QDR with benzine. The lines represent the results of calculations.

conditioned by the absence of measurable absolute reproducibility at the resonator structure reassembling, the measurement procedure is carried out as follows. At every value of $r_2 - r_1$, firstly, the frequency f_a is measured for the QDR with air-filled groove, then the frequency f_{liq} is measured for the resonator with liquid, following which the frequency shift $\Delta f = f_{liq} - f_a$ is determined and applied to the plot (Figure 7).It is worthy to note, that the horizontal line in Figure 7 corresponds to air filling of the ring groove. One can see that Δf **decreases** with the availability of benzine filling (ε'=1.9). However, water presence within the QDR gives an opposite effect, namely, Δf **increases** with the increase of water volume. The latter indicates that as if we have some substance with $\varepsilon'<1$ which is placed in the area of electromagnetic field concentration. The direct calculations based on the dispersion equation for the radially two-layer QDR with CEP [8, 10] lead to the conclusion that for adequate description of Δf dependence on $r_2 - r_1$ in the case of water, it is necessary to take in account known dielectric properties of water in K_a-band ($\varepsilon' = 20$ and $\tan\delta = 1.7$). In this connection it is interesting to note that the sign of Δf in QDR with a metal ring within the ring groove is positive also that seems some proof of that electromagnetic field structure is nearly the same in these both cases.

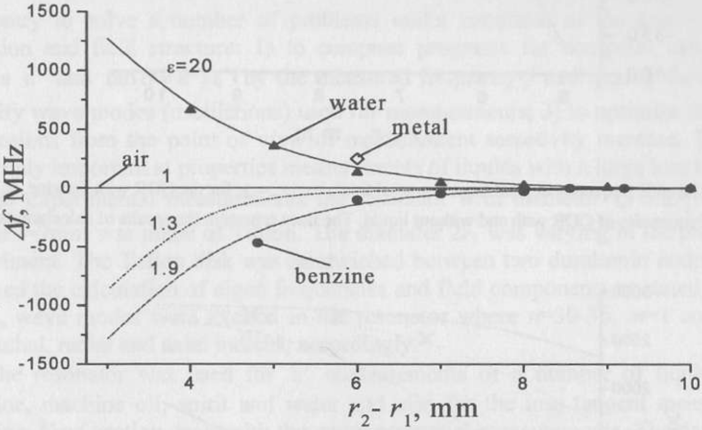

Figure 7. Frequency shift $\Delta f = f_{liq} - f_a$ as a function of difference $r_2 - r_1$. The lines represent the results of calculations.

Without accurate calculation of Δf we could came to conclusion that a thin layer of water with a negative sign of permittivity exists near the boundary with Teflon wall, and such a conclusion has been made in [13]. It was based on calculating extraordinary occurrence at work with software. Annino and Cassettary [14] pointed out the error in [13] (see Comment and Reply on the Comment [14]). The discovered effect is not observed for such liquids as benzine. Probably, other high-loss tangent liquids will show the same effect as water. A phenomenon of the "anomalous" frequency shift in QDR with water has been discovered due to application of a dielectric resonator with higher order traveling azimuthal waves, i.e. WG modes [7,8,10,11], in the field concentration area of which an interface of solid-state dielectric and water can be placed. Recently effect of "anomalous" frequency shift of resonator with water has been confirmed in experiments with QDR containing cylindrical capillary filled with water [15]. The discovered feature is caused by larger dielectric permittivity of water than one of material which the resonator made of and in addition by the higher imaginary part if water permittivity than the real. Under these conditions as accurate calculations show electromagnetic field distribution is sensitive enough to presence of water layer in the resonator. The feature is rather attractive for physical study in microwave electrodynamic structures because it is uncommon. On the other hand, it is quite possible that the feature can be useful at measurements of high-loss liquids.

7. Whispering gallery modes in liquids with small loss tangent

The study of the radially two-layered QDR properties promoted to the authors to use such a resonator for microwave characterization of above-described liquids. An attempt to excite WG modes directly in liquids became a next step. Present work considers the excitation of GW modes in two liquids, namely, machine oil and benzine. The experimental set-up enables one to measure eigen frequencies f and Q-factor of the QDR [11]. The measuring cell is a thin cylinder with external diameter D=78mm, height l=6mm and wall thickness h=1mm made of foam plastic ($\varepsilon' \approx 1$). This material turns out to be convenient for carrying out measurement of oil. Unfortunately, porosity and partial solubility of the foam plastic are taking place for the case when we use benzine. Measurements of benzine and machine oil were carried out in the open QDR with and without the duralumin CEP [16]. The former variant is the best one because it allows one to find field structure in the resonator from Maxwell equations directly and, hence, to calculate ε' and ε'' of liquids with better accuracy than it was possible earlier. The resonance curve oscillogram of the open QDR with WG modes in one of liquids is presented in Figure 8.

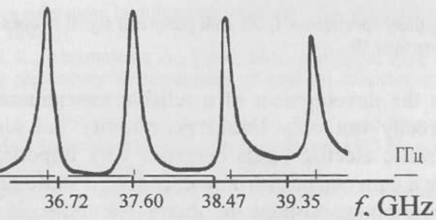

Figure 8. The resonance curve oscillogram of the open QDR with WG mode waves in benzine.

The analytical treatment of experimental values of frequencies and quality factors of the open QDR with clean low-octane benzine gives the values ε'=1.88 and $tan\delta$=3.3·10^{-3} at frequency f_o =40GHz that agrees well with the data in section 5. In case of the machine oil, the dispersion equation allows one to obtain ε'=2.18 and Q-factor measurement of the open QDR allows one to find $tan\delta$ = 2.8·10^{-3}. Measurement errors of permittivity and loss tangent make up $\Delta\varepsilon'/\varepsilon'' < 1\%$ and $\Delta tan\delta / tan\delta < 15\%$. The latter is conditioned in the main by the frequency instability of a microwave generator in the network scalar analyzer. The WG mode excitement directly in liquids simplifies considerably the measurement technique in case of liquids with low and moderate values of loss tangent and allows one to enhance the measurement accuracy of absolute values of liquids complex permittivity in the microwave range.

8. On the possibility to study nonlinear dielectric properties of liquids

Strictly speaking, the ideal physical systems with linear response dependence on external fields are absent in nature. Studies of nonlinear properties of substances give valuable information about the interaction mechanisms of the fields with substances. In this respect many works have been carried out in solid-state physics. Suffice it to remember such topics of modern physics as nonlinear optics, quantum radiophysics and electronics, plasma physics etc. Apparently the nonlinear properties of liquids were rather poorly studied. One of the reasons of this is the complexity of both the experimental studies and development of suitable theoretical models. Here, water provides a striking example of this. Many works were devoted to its study, however, a microscope model of the sub-molecular structure of water has not been developed yet.

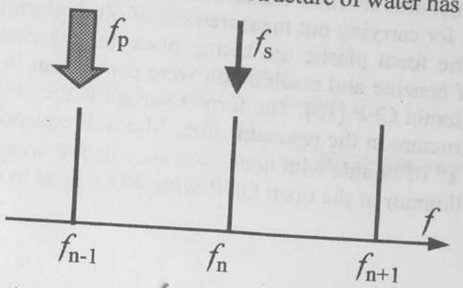

Figure 9. Whispering gallery spectrum of QDR with pump and signal frequencies, *n* is azimuthal index which is more than 10.

In this connection the development of a reliable measurement technique allowing one to determine directly not only liquid permittivity but also its dependence on electromagnetic and static electric fields becomes very important. In this respect the QDR with CEP can be a convenient instrument. In fact, a static field can be created with the help of CEP by applying voltage to them. Naturally, if there is an available equipment providing a maximum difference of potentials U_{max}, one can achieve electric field $E_{max}=U_{max}/l$. It is clear that the field value E_{max} grows up with increase of ε' because l decreases in proportion to $\sqrt{\varepsilon'}$. One can conveniently measure dependence of ε' on high-frequency field E_ω by using the pumping technique where a substance is acted by a field at a certain frequency f_p and a response is measured at another, i.e. biased, frequency f_o. Such an approach is easily realized with the use of the QDR because it has a quasi-equidistant spectrum of resonant frequencies. One of them is taken as the signal frequency f_o and another as the pump frequency f_p. Here, it is convenient to use inequality $f_p<f_o$ both for the frequency isolation between two channels and the guarding of receiver from a high-power signal at the frequency f_p (Figure 9). Such an approach has been earlier developed for the study of nonlinear properties of high- temperature superconductors [17].