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TUTORIAL AND REVIEW PAPER

Whispering gallery mode resonators in microwave physics and technologies

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We review the main results of the development of whispering gallery mode (WGM) resonators and their unique applications due to their quasi-optical functionality. Several types of advanced WGM resonators are proposed by the authors. The theoretical results are described for the resonators with an analytical solution of the electromagnetic problems. Special emphasis is given to the interaction of moving charged particles and waves of cylindrical resonators. Important aspects are described concerning the developed sapphire resonators, for which an exact solution can only be found by using specially designed computer program products. A separate section of the paper is devoted to application aspects of the WGM resonators. In particular, it describes advanced solutions for overcoming the problems of measuring the small microwave (MW) surface impedance of unconventional superconductors in the form of large-area thin films and small samples under study. In addition, a demonstration of accurate complex permittivity measurements of small volumes of lossy liquids is provided. Special emphasis is given to highly stable MW signal sources, namely Ka-band transistor-based feedback oscillator and solid-state maser WGM oscillators. Recently obtained results are presented of experimental studies of the auto-oscillatory system developed on the basis of the WGM resonator with relativistic electron beam.

Keywords: New and emerging technologies and materials, Characterization of material parameters, Microwave measurements

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I. INTRODUCTION

The progress of microwave (MW), millimeter (mm), and submillimeter (submm) wave ranges is directly related to the development of the appropriate scientific and engineering approaches, devices, and techniques. Experience with quasi-optical technology enables advanced passive mm and submm elements to be designed on the basis of high-*Q* quasi-optical resonators. The dielectric resonators (DRs) excited at whispering gallery modes (WGMs) are promising representatives of such resonators. Because WGM resonators are quasi-optical DR (QDR), the acronyms QDR and WGM resonator are synonyms. In this paper, we use the acronym WGM resonator – commonly accepted in the English-speaking scientific community.

It was noted in [1, 2] that there are weakly damped azimuthal modes in the round dielectric rod with relative permittivity values ε_1 in the range of 2–10. From the view point of geometrical optics, these modes are formed inside the dielectric by waves that are excited in a cylindrical DR with a curvature radius of ρ_0 at angles greater than the angle of total internal reflection from the resonator circumference and are characterized by large values of azimuthal indices n. The electromagnetic field decays outside the dielectric. This results in ultra-small radiation losses and consequently in the high *Q*-factor of WGM resonators. Dielectric WGM resonators also demonstrate high mode stability. For the first time, an abnormally low damping of waves propagating along the circumference surface was observed for acoustic waves traveling along the inner wall of the circular gallery [3]. Therefore the azimuthal modes excited under the condition $\omega\rho_0/c < n < \sqrt{\varepsilon_1}\omega\rho_0/c$ [1] were termed WGMs. Here ω and c are the angular frequency of the modes and the light velocity, respectively. We now show that not only passive but also active devices can be developed on the basis of high-*Q* WGM resonators.

A) Brief historical background

In the 1960s, experts in the MW technology put forward the hypothesis that resonators may be designed on the basis of dielectric materials without the application of metal walls as reflectors of electromagnetic energy. The maser developers used a rutile parallelepiped without additional metal mirrors as a resonator. The permittivity of a rutile crystal is about 100, and the dielectric loss is very low [4, 5]. Such resonators were excited at the lower modes. At the same time, the first results were reported on experiments with DRs in the form of a sphere. An interesting fact should be noted: the fundamental mode was not excited in the resonators, but the

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WGMs were excited [6]. These experiments were forgotten for about 30 years.

In the mid-1960s the question of the excitation of the WGMs in ruby rods used in lasers appeared again. In [7], such modes were considered to be undesirable; therefore the modes were strongly damped. In contrast, S. N. Vlasov showed the existence of WGMs as weakly damped modes in 1967 [1]. In the same year, J.R. Wait published his results on theoretical studies of WGMs existing in a dielectric cylinder [2]. In the early 1970s, work on studying cylindrical disc WGM resonators was initiated by V.F. Vzyatyshev at Moscow Power Engineering Institute. The resonators were in the form of short cylindrical rods (disc resonators) without metal plates at the ends. In 1980, it was found that in the ring DR made of sapphire *Q*-factors of the order of 6×10^8 can be achieved even without superconducting coatings [8].

In the mid-1980s, the development of mm-wave solid-state oscillators with quasi-optical resonators of two kinds, namely DRs excited with WGM and Fabry–Perot, was started at the Institute for Radiophysics and Electronics, National Academy of Sciences of Ukraine (IRE NASU). The researchers devoted special attention to the cylindrical disc WGM resonators, which were used as the resonant system of the oscillator. Later their activities concentrated on the electrodynamics of mm-wave WGM sapphire resonators, the development of measurement techniques for condensed matter mm-wave characterization and exploring the possibility of fabricating the MW active devices on the basis of these resonators. Since the late 1980s and early 1990s, WGM resonators have been developed intensively and also studied in a number of other countries, such as France, Australia, Poland, and Italy from the point of view of using resonators in different areas of MW physics and engineering, primarily for measurement techniques and oscillator technologies.

B) Main problems under considerations

In this paper, the authors present an overview of the main results, obtained mostly this century, of studies and applications of QDRs. Advanced types of WGM resonators including those proposed by the authors are considered. At first, the results of the theoretical study are given for the resonators, which allow the corresponding electromagnetic problems to be solved analytically, i.e. for the cylindrical disc, spherical, and isotropic hemisphere resonators. A certain emphasis is also given to the interaction of the fields of moving charged particles and waves of cylindrical resonators. After this, an important aspect is the sapphire resonators developed and produced by the authors, which can only be analyzed using special computer program products. Therefore, in addition to cylindrical discs, the experimental data are presented for the resonators in the form of a hemisphere and truncated cone. Radially slotted and radially layered cylindrical discs and also cylindrical discs with a microfluidic channel are studied.

The next section of the paper is devoted to application aspects of the WGM resonators. In particular, it describes how the problems of measuring the small MW surface impedance of unconventional superconductors in the form of the large-area thin films and small samples under study can be overcome. A demonstration of accurate complex permittivity measurements of lossy liquids in small volumes is provided. In addition, emphasis is given to high-stability MW signal sources, namely Ka-band transistor-based feedback oscillators and solid-state maser WGM oscillators. The first results on experiments studying the auto-oscillatory system based on a WGM resonator with relativistic electron beams (REBs) are also presented.

II. TYPES OF WGM RESONATORS

A) Resonators with derived analytical solutions

1) RESONATORS WITH CYLINDRICAL SURFACES

The theory of eigenmodes in anisotropic cylindrical DRs with conducting endplates (CEPs) has been developed further [9–17]. Here the characteristic equations for the DR and expressions for the components and energy of the electromagnetic field were obtained, which allow us to study the spectral and energy characteristics of resonators, taking into account energy losses in the materials of which they are made [10, 11, 15, 16–19]. The conditions for separating the modes were also defined [11–13]. This condition and the solutions of the characteristic equation allow resonator modes to be unambiguously identified: HE_{nsl} or EH_{nsl}, where *n*, *s*, and *l* are the azimuthal, radial, and axial mode indices, respectively. It was shown that in a cylindrical DR with perfect CEP only axially homogeneous oscillations of the E-type exist in the form of TM_{ns0} modes. In [9, 16], a method for determining the spectral and energy characteristics of DR without CEP was suggested.

The analytical solution of the unloaded *Q*-factor of the anisotropic resonator with HE or EH modes was developed and is of interest for measuring the small values of the surface resistance or, in the general case, the surface impedance of conductors and superconductors in the mm-wave range [15, 17–19]. The integral equation for the DR frequencies was obtained taking into account the finite conductivity of the endplates [11, 13, 17]. The resulting expression allows the surface impedance of the CEP under study to be determined by using the experimentally measured complex resonance frequency of the resonator [9, 17].

The spectral and energy parameters of DRs made of different materials and CEPs with both perfect and imperfect conductivity were found [9, 14]. The anisotropic (Al_2O_3) resonator with CEPs of HTS ($YBa_2Cu_3O_{6.95}$) for the mm waveband was studied in [10, 13]. It was shown that the resonator frequencies differ by 5–20 MHz from the frequencies of the resonator with perfect CEPs utilizing the same modes. It was found for the higher modes, when radiation losses are negligible, that the resonator *Q*-factor is limited by the level of $\tan\delta_1$, where $\tan\delta_1$ is the dielectric loss tangent. The resonator maximum *Q*-factor is observed to exceed the level of $(\tan\delta_1)^{-1}$ as a function of the azimuthal index *n* and this effect can be considered as a criterion for the choice of the resonator parameters.

A high-precision computation of the spectral characteristics of DR with CEP is obtained by using the characteristic equations when the ratio $D/2\rho_0 > 1.1$, where *D* and $2\rho_0$ are the diameters of the CEP and resonator, respectively. This fact was established by comparing the experimentally measured resonance frequencies of a Teflon resonator with aluminum CEPs of different diameters D and calculated frequencies of DR with surfaces that have $D = \infty$ [20].

This theoretical approach was used for solving the electrodynamic problems concerning WGM resonators with cylindrical surfaces, namely for the resonator with mutually orthogonal directions of the anisotropy axis and the longitudinal axis [9] and the semi-cylindrical resonator [21]. As previous experiments showed, the radially layered resonators can be of practical interest [22]. Therefore the electrodynamics of the resonators with perfect CEPs was developed [23–26]. Within the framework of electrodynamic analysis, the theory of the radially two- and three-layered DRs (whose layers are anisotropic materials) was developed. The solutions of the characteristic equation allow the resonator modes to be identified unambiguously [25, 27].

The maximum discrepancy between the calculated and measured frequencies of the two-layered resonator is <1% [27]. When the radius of the inner layer is changed, the field distribution of the energy density and the electric strength of the axially homogeneous mode shows dynamics that are not obvious [9].

The electrodynamics of radially three-layered DRs has been developed in [9, 23, 24, 28]. The middle layer represented the substances with low and high losses. The resonator with the inner and outer layers made of Teflon and with the middle layer filled with various substances was considered theoretically. The frequencies and Q-factors of the resonator with $\mathrm{TM}_{36\ 1\ 0}$ mode were studied for different thicknesses of the middle layer and its location along the radius [24, 28]. Rigorous and simplified methods for determining the electrophysical parameters of materials with low losses were applied when they occupy small volumes.

2) RESONATORS WITH SPHERICAL SURFACE

The electrodynamics of DRs with spherical surfaces was also considered: anisotropic spherical and isotropic spheroid DRs were developed [9, 29, 30]. Here the azimuthally inhomogeneous modes in isotropic spherical and spheroidal DRs were studied for the first time. Characteristic equations were obtained, whose solutions determine the resonant frequencies. It was shown that the degeneracy of the mode frequencies, which are inherent for isotropic spheres, is removed under the influence of anisotropy [29] or small ellipticity [9, 30]. In these resonators, the transformations of TE and TM modes result in quasi-TE and quasi-TM modes. The eigenfrequencies of the sphere, in which $\varepsilon_{-1}/\varepsilon_{+1} << 1$, where $2\varepsilon_{\pm 1} = \varepsilon_{||1} \pm \varepsilon_{\perp 1}$, are determined by solving the characteristic equations given in [29]. It was shown that the resonator frequency unambiguously identifies the quasi-TM_{mns} or quasi-TE_{mns} mode, where m, n, and s are the polar, azimuthal, and radial indices, respectively. With increasing azimuthal index, the frequencies of the resonator with TM_{mns} modes increase and those of the resonator with TE_{mns} modes decrease when the other indices are the same [29]. The ratio between the indices of the resonator mode and the field variations along the spatial coordinates is not an obvious value for the corresponding mode. It should be noted that the polar index m is determined taking into account the field variations $\bar{p}$ over an angle of $\theta : m = \bar{p} + n - 1$.

An analysis was made of a spherical semiconductor resonator [31]. The eigenmodes of the semiconductor sphere of indium antimonite were studied for the first time. It is shown that in the resonator besides high-frequency volume oscillations there are also surface oscillations. Inside the sphere, their amplitude decays exponentially along the radius from the resonator surface. For large values of the polar index, whose values are greater than zero, a surface oscillation becomes like a plasmon on the plane boundary of the semiconductor.

The hemisphere resonator with CEP is of great practical importance for MW measurements. The field and spectral characteristics were first studied theoretically for this type of resonator with a perfect CEP [32–34]. The characteristic equations of such a resonator immersed in an isotropic medium were obtained and the field components of independent TM and TE modes were defined [33]. It is shown that the separation of TM and TE modes follows from the boundary condition on the conductive surface of the resonator. For TE modes the sum of azimuthal and polar indices $(n + m)$ has even values, and for TM modes it has odd values. This results in the frequency $(m + 1)$-fold degeneracy of TE modes by the azimuthal index n. The TM modes have m-fold frequency degeneracy because the azimuthal TM mode $(n = m)$ does not exist in the resonator. In the resonator, the type of azimuthally homogeneous oscillation $(n = 0)$ is set by the evenness of the polar index m. The methods for experimentally determining the angular indices of the resonator modes were developed in [9, 33]. They are based on the study of the mode field distribution on the spherical surface of the resonator. The field variations over the angular coordinates are associated unambiguously with mode indices. The number of field variations $\bar{p}$ in the polar angle θ satisfies the condition $\bar{p} \geq (m - n + 1)/2$ and has the value rounded to the nearest integer in the line of increase. In practice, it is convenient to use the designation of mode by analogy with the disc cylindrical resonator, e.g. instead of TM_{mns} or TE_{mns} these modes are designated $\mathrm{TM}_{ns\acute{p}}$ or $\mathrm{TE}_{ns\acute{p}}$ where $\bar{p}$ is the number of field variations in the polar angle.

It is shown that for the most efficient excitation of the resonator mode the excitation source has to be located close to the hemisphere surface in point with the polar coordinate $\theta_{\max}$, which corresponds to the field maximum. The characteristics of the resonator were determined when it is placed in the environment of various substances with and almost without losses [33]. It is shown that the small changes in the permittivity of the environment lead to significant changes in the resonator eigenfrequency and the Q-factor.

The integral equation describing the effect of the finite flat conductive surface on the eigenfrequencies of the hemisphere was obtained in [34, 35]. It was found that the frequency tuning of the resonator is possible relative to the frequency of the resonator with perfect CEP if the flat surface of finite conductivity is used.

The forced oscillations excited by radial magnetic dipole in the hemisphere placed on a CEP were studied theoretically in [32], where it was shown that the radial magnetic dipole excites only the TE modes. When the point source excites the resonator there is $(m + 1)$-fold frequency degeneracy over the azimuthal index n of both the forced and eigen-TE modes. The resonance conditions are achieved when the frequency of dipole radiation reaches the resonator eigenfrequency. The oscillations in the hemisphere can be effectively excited when the magnetic dipole is placed in the field maximum of the resonator eigenmode.

In [36], the theory of the eigenmodes of radially layered spherical resonators was developed when their layers are isotropic. These resonators were proposed for determining the complex permittivity of materials.

3) INTERACTION OF THE FIELDS OF MOVING CHARGED PARTICLES AND EIGENWAVES OF CYLINDRICAL STRUCTURE

One of the most urgent problems of modern MW physics is the study of the fundamental properties of solid-state structures that contain nanoscale fragments. As a rule, studies of the excitation mechanisms of electromagnetic waves when the charged particles move in various electrodynamic systems form the basis of electronics. In this case, a number of the basic characteristics of structures are included in their dispersion equations. Energy loss of a charged particle per unit time for the excitation of waves and/or oscillations in the system is the important information characteristic. In [37], using Maxwell's equations and based on an integrated approach (analytical and numerical) the energy losses of a charged particle moving along a spiral path over the surface of the cylinder, which is a dielectric or metal, were determined. The conditions were found under which there is electromagnetic gyrosynchrotron radiation in the system. Dispersion equations were obtained characterizing the eigenmodes of semiconductor (or dielectric) cylinders with a layer of two-dimensional (2D)-electron gas on a side surface, and the energy losses of a charged particle were determined when it moves along a spiral path around such a structure [38]. The dispersion dependencies of slow eigenwaves of the system were obtained, and the energy losses of a particle moving in an external magnetic field were found when the field vector is parallel to the longitudinal axis of cylindrical structure symmetry. The structures with and without the plasma layer were studied when their frequencies were in the THz range. The influence of a surface plasma layer of nanoscale thickness on the eigenfrequencies of semiconductor and dielectric cylinders was studied.

The formula for the energy loss of the particle per unit time was obtained and analyzed [37, 38]. It should be noted that in [38] the formula has a universal character. The formula allows the energy losses of the charged particle to be obtained when it rotates and/or moves translationally, as well as losses of the charged ring encircling cylinder that is also moved translationally. It can be used to describe the energy losses at mode excitation in various cylindrical structures with 2D electron gas, as well as in a semiconductor cylinder.

The frequencies of excited modes with the azimuthal indices n in the range of 0–100 in the semiconductor and dielectric cylinders with 2D-gas at the side surfaces were found, as well as in the cylindrical plasma 2D-layer and semiconductor cylinder. The radiuses of structures are 0.5 cm. The excitation of modes was performed by the charged particle that is moved translationally with a velocity of $0.8c$ (where c is the light velocity) along a spiral path with a radius of 0.51 cm in various external longitudinal magnetic fields. The parameters of the structures were stipulated by the choice of the THz frequency range as an operating band. The excited modes can be selected by the external magnetic field.

B) Developed and fabricated sapphire resonators

1) CYLINDRICAL DISC, HEMISPHERE, AND CONE RESONATORS

Dielectric WGM resonators have been widely used for MW and mm-wave studies of condensed matter, particularly unconventional superconductors [10] and biological liquids [22]. Superconductors have small losses; therefore resonators made of a single-crystal sapphire are applied to study the superconductor properties because sapphire has the least losses at cryogenic temperatures in the mm-wavelength range.

In order to study superconducting films, a disc resonator with CEPs is most suitable in terms of measurement accuracy and sensitivity where CEPs are made of the test films [10] (Fig. 1a). This is due to the possibility of a rigorous solution of the electrodynamic problem (see subsection A1 in Section II). This resonator and E_Z-component of the electric field are shown in Fig. 1a; the resonance frequency spectrum is shown in Fig. 1b. Calculations of both the resonator spectrum and the electric field distribution for TM_{nso} mode were performed using the CST Microwave Studio package.

Unfortunately, as an mm-wave surface impedance sensor this resonator has the following disadvantage: two superconducting films have to be used. As a consequence, the measured value of the surface impedance is an average of two films. Structures with one conducting plane would be helpful to eliminate this disadvantage. One such structure is a hemisphere with a CEP [35]. This structure also allows a rigorous solution of the electrodynamic problem (see Section II.A2), but only for an isotropic dielectric substance which is made

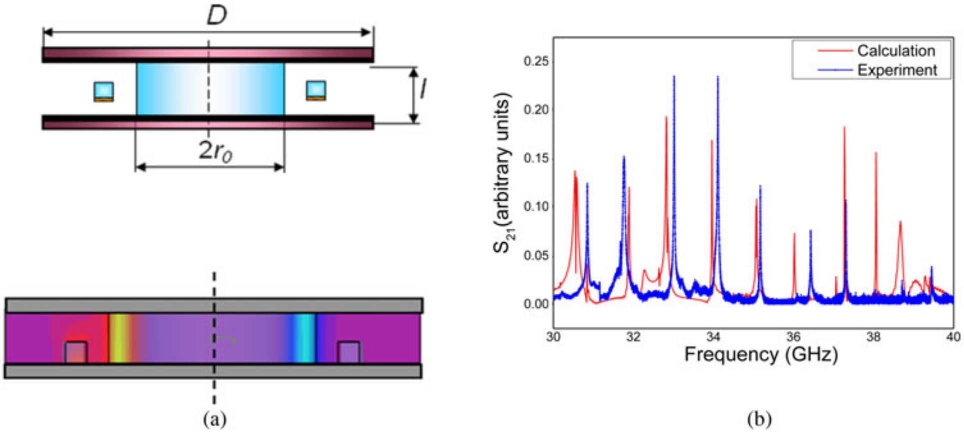
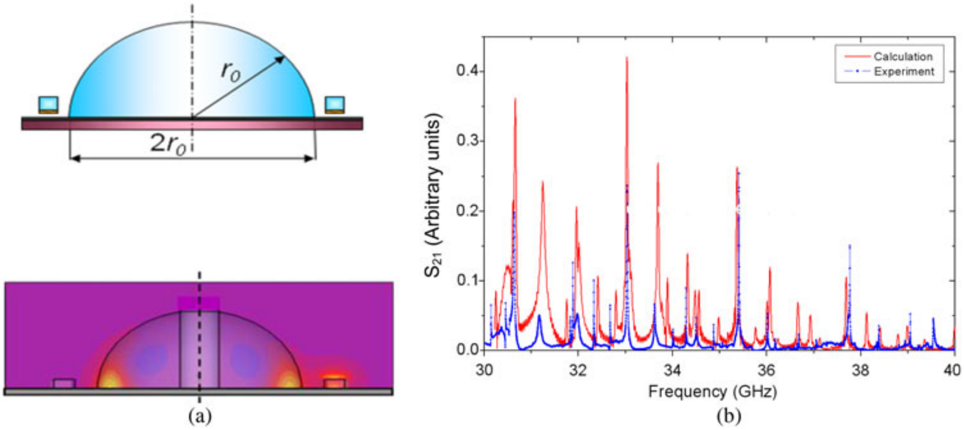


Fig. 1. Cylindrical disc with HTS films and calculated E_z-component of electric field distribution (a); experimental and calculated spectra of the resonator (b).



(a) (b)

Fig. 2. Hemispherical resonator with HTS films and calculated E_z-component of electric field distribution (a) experimental and calculated spectra of the resonator (b).

of a resonator. The sapphire is anisotropic dielectric; therefore, the measurement structure requires numerical methods for solving the electrodynamic problem or calibration procedure. This resonator and E_Z-component of the electric field are shown in Fig. 2a; the resonance frequency spectrum for HE_{nsl} modes is shown in Fig. 2b.

One of the disadvantages of hemispherical resonators is that they are complex to manufacture. Therefore, in cases where extreme measurement accuracy and sensitivity are not required, e.g. in the study of high-T_c superconductors at $T = 77$ K, a structure based on a truncated cone may be used [39]. The cone resonator with a CEP and E_Z-component of the electric field is shown in Fig. 3a; the frequency spectrum for HE_{nsl} modes is shown in Fig. 3b.

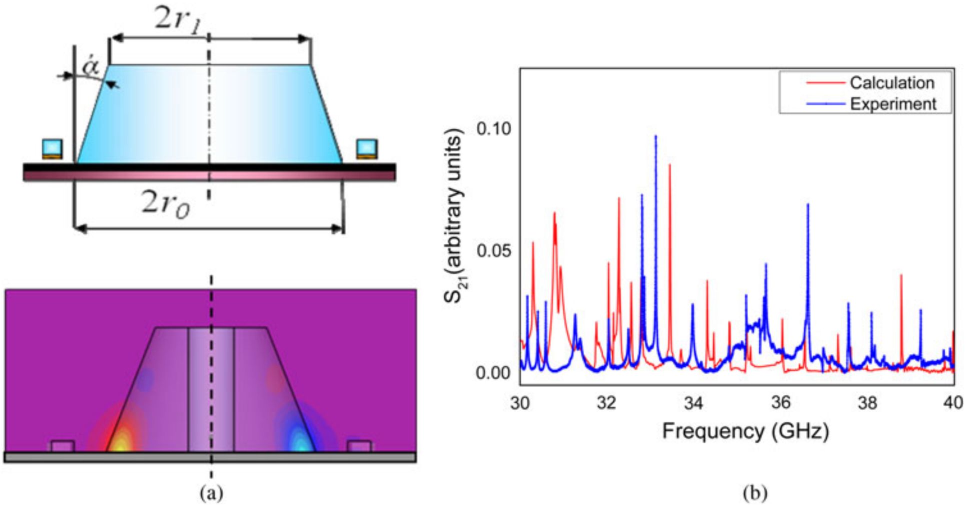
A comparison of the characteristics of the three resonators considered above as MW impedance sensors is presented in Section III. A1 (data in Table 1 are given for $f = 35$ GHz).

2) RADIALLY SLOTTED, RADIALLY LAYERED DISCS, AND CYLINDRICAL DISC WITH MICROFLUIDIC CHANNEL

Using these resonators with CEPs, which are also the HTS films under study/test, it is impossible to study the MW properties of single-crystal superconductors, as they are much smaller than the base of the resonator. That is why the disc resonator was modified to study the single crystals of unconventional superconductors [40]. The disc resonator with a radial slot and the E_Z-component of the electric field are shown in Fig. 4a, and the spectrum for TM_{nso} modes is shown in Fig. 4b.

Utilizing this resonator, the superconductor single crystals can be studied not only when the slot is completely filled. A sufficiently small value of the radiation Q-factor ($Q_{rad} \leq 10^5$) does not allow the radiation loss to be neglected in finding the absolute value of the surface resistance, which leads to a significant measurement error, because it is impossible to accurately determine Q_{rad} for real structures. As a rule, the radiation Q-factor is evaluated by calculation. Thus, the resonator is a convenient tool for the study of the temperature dependence of the surface resistance, but only if it is normalized to a reference value.

Studies of biological fluids, normally aqueous solutions, i.e. condensed matter with great losses, may be performed using a radially two-layer disc cavity [41], which is a modification of the sapphire disc resonator with CEP. The rigorous solution of the electrodynamic problem is one of the advantages of this structure. However, it has several disadvantages,



(a) (b)

Fig. 3. Conical resonator with HTS films and calculated E_z-component of electric field distribution (a); experimental and calculated spectra of the resonator (b).

Table 1. Characteristics of the three resonators considered above.

	Q at T (K)			Q_{rad}	$R_{s\ min}$	$\delta R_s/R_s$	A_s
	300	77	4.2		Ω	%	1/Ω
Cylindrical disc	4.3×10^4	4.6×10^5	1.1×10^6	5.9×10^9	5.1×10^{-7}	2.0 (4.2 K)	2.92×10^{-3}
Hemisphere	4.5×10^4	5.6×10^5	4.6×10^6	1.1×10^{10}	1.4×10^{-6}	1.8 (4.2 K)	1.08×10^{-3}
Truncated cone	4.1×10^4	2.1×10^5	2.4×10^5	5.1×10^7	2.6×10^{-5}	2.5 (77 K)	2.08×10^{-3}

namely: (i) the rather considerable loss in the CEP results in a decrease in the *Q*-factor in comparison with the disc without CEP; (ii) the liquid under test has a rather large volume; and (iii) the complexity of the practical implementation of sealing engagement between the dielectric disc and metal endplates.

These disadvantages can be eliminated by using a disc resonator with a microfluidic channel without CEP. Despite the impossibility of a rigorous analytical solution of the electrodynamic problem, this structure can be applied to the study of biological fluids using a special calibration procedure [42].

Examples of important applications of the resonators in the form of radially slotted, radially layered discs, and cylindrical discs with microfluidic channels are given in the following section.

III. APPLICATIONS OF WGM RESONATORS

A) MW characterization of unconventional superconductors

During the last few decades, many materials with various and indeed surprising properties have been discovered. An important place among them is occupied by a novel family of superconductors (HTS cuprates, Fe-pnictides, Fe-chalcogenides, etc.). The unusual and unknown nature of their superconductivity and possible prospects for application led to a plethora of experimental and theoretical works. The distinctive feature of these materials is a very small level of MW losses. This peculiarity, attractive to MW engineers, results in difficulties for the experimental study of superconductors and demands the development of special high-*Q* resonators.

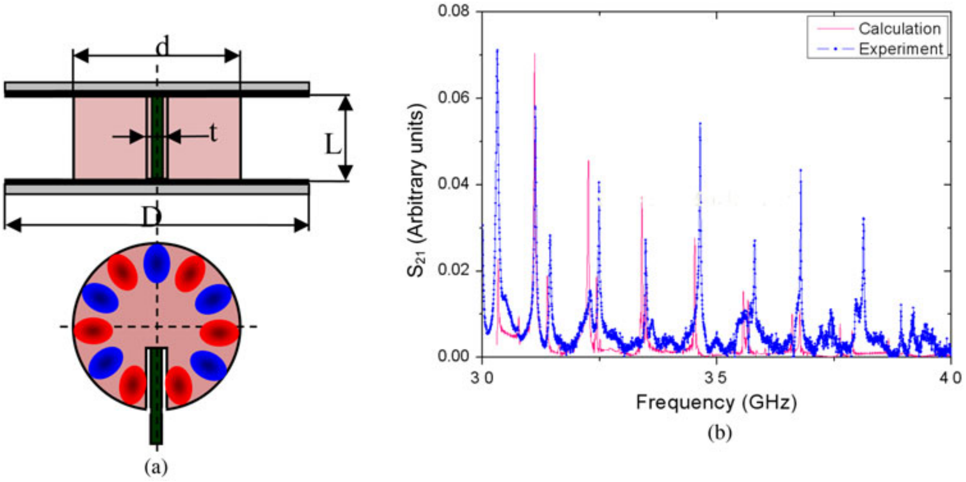
Studying the MW properties of superconductors, as well as all the conductors, is convenient in terms of surface impedance

$$Z_s = \frac{\sqrt{i\omega\mu_0}}{\sigma} = R_s + iX_s. \tag{1}$$

R_s and X_s are the surface resistance and reactance, respectively. For superconductors, the complex conductivity is $\sigma = \sigma_1 - i\sigma_2$, where σ_1 and σ_2 are the quasi-particle and superfluid component conductivity and here $R_s \neq X_s$. The R_s and X_s measurements are important both for fundamental physical studies and technical applications.

For the classic MW range with $f < 25$ GHz, the standard technique based on sapphire (Al_2O_3) resonators was proposed [43]. In the mm-wavelength range ($f > 25$ GHz), the dimensions of DRs with lower modes become unacceptably small and their *Q*-factor drops. The higher azimuthal order modes, i.e. WGM in QDR, have the highest *Q*-factor. They have acceptable dimensions in the mm-wave range and are suitable for measuring the properties of HTS films [10]. Especially measurements in the mm range make it possible to achieve greater accuracy due to increased surface resistance in proportion to f^2. The idea of using WGM to study high-temperature superconductors was put forward in the late 1980s [44], and the first results in this direction were reported by the authors in the early 1990s with respect to HTS ceramic properties [45].

The challenge of performing accurate measurements of Z_s for unconventional superconductors becomes very relevant in



(a)

(b)

Fig. 4. Radially slotted disc resonator with a small superconductor sample placed in the slot and calculated E_z-component of electric field distribution (a); experimental and calculated spectra of the resonator (b).

two cases, namely, not only for: (i) small samples, which are, as a rule, single crystals, but also for (ii) unpatterned, i.e. large-area films. The first is mainly important for physical research, the second for both MW applications and the study of the nature of superconductivity itself. The authors developed the WGM resonator-based measurement technique for surface impedance characterization of unconventional superconductors in the form of thin films [10] and single crystals [40].

1) LARGE-AREA THIN FILMS

In this case, a problem has to be solved considering the following conditions [46]: (i) measurement of Z_s (at least, R_s) without calibration procedure, (ii) large area of unpatterned films with acceptable limitations of linear dimensions in the a–b plane of the sample, (iii) small splitting of the resonance line obstructing the accurate measurement of the resonator Q-factor in the case of using the known technique, (iv) control of coupling the resonator with feeder transmission lines in the process of cryogenic cooling of the resonator with a sample, and (v) minimization of radiation losses.

For Z_s measurement without a calibration procedure, it is necessary to find an analytical solution to the electrodynamic problem of WGM resonators with the sample under test. At present, this condition corresponds to only a cylindrical WGM resonator with two CEPs also considering the use of a single-crystal sapphire as the anisotropic dielectric [10] (see Section II.A.1).

R_s can be found using a general expression [10]

$$R_s = \frac{Q^{-1} - k\tan\delta - Q_{rad}^{-1}}{A_s}, \tag{2}$$

where coefficients k and A_s and radiation Q-factor Q_{rad} are calculated analytically (only for cylindrical disc resonator). The value of Q_{rad}^{-1} in (2) can be very small in comparison with Q^{-1} and $k\tan\delta$, and therefore it can be omitted. At low temperatures ($T \ll T_c$), losses in both the superconductor and dielectric of the resonator can become close to Q_{rad}^{-1}. In this case, the problem is solved when the radiation Q-factor can be excluded (e.g. for measurement of R_s variation) [40] or the Q-factor can be found by means of analytical calculations [10] or numerical experiments.

In practice, it is convenient to use WGM resonators in the shape of a hemisphere [36] or truncated cone [39], as they have only one CEP and hence one sample under test [47]. In this case, the reference sample has to be used. The application of HTS films as the CEP of the resonator allows us to overcome restrictions on the size and shape of the substrate with the film. It is important to fulfill the following condition: that a circle with a diameter greater than one of the dielectric discs could fit into the film plane of more than about 2 mm (for Ka-band).

Measurement of X_s is the difficulty inherent in all resonator methods, namely, the inability to accurately determine the eigenfrequency of the resonator with perfectly CEPs. Therefore, as a rule these measurements determine the change in the surface reactance $\Delta X_s(T)$ of a sample by the resonator frequency shift $\Delta f(T)$ caused by a temperature change of the sample:

$$\Delta X_s(T) = \frac{-2\Delta f(T)}{fA_s}, \quad \omega = 2\pi f. \tag{3}$$

Then, knowing the London penetration depth $\lambda_L(0)$ at $T = 0$, the reactance can be obtained

$$X_s(T) = \omega\mu_0\lambda_L(0) - \frac{\Delta f(T)}{fA_s}. \tag{4}$$

It should be taken into account that a general shift $\Delta f(T)$ also contains the components as a result of the temperature dependence of the permittivity and dimensions of the resonator.

Partial removal of double degeneracy of whispering gallery waves represents a serious difficulty in using WGM resonators as HTS surface impedance sensors. The effect is particularly strong when the Q-factor reaches values of 10^5–10^6 and above (Fig. 5). In this case, the problem of finding the exact unloaded Q-factor and frequency of the resonator arises because the measured resonance line becomes non-Lorentzian. This problem was solved first for a simple special case, when the frequency response of the resonator is symmetrical [48], and then for the more general case of asymmetrical response including the influence of the frequency response of feeder transmission lines in the coupling elements of the resonator [49]. For this, first of all, a special program was developed for computer processing of the measured frequency response of the resonator in order to accurately determine the Q-factor and resonance frequency.

When the temperature changes from low to T_c the resistance R_s of the superconductor changes by several orders of magnitude, and therefore the unloaded Q-factor varies within a wide range, making it necessary to adjust the coupling of the resonator and feeder transmission lines in the process of impedance measurements. Usually this problem is not easy to solve. The application of dielectric waveguides (or quasi-imaginary lines) arranged in the form of a truncated letter Λ allows the coupling with WGM resonator to be controlled during operation at cryogenic temperatures (Fig. 6).

In practice, the authors use the hemispherical sapphire WGM resonator (e.g., see [50, 51]). Figure 7 shows $R_S(T)$ dependence on temperature for the studied epitaxial $YBa_2Cu_3O_{7-\delta}$ film of 600 nm thickness sputtered onto a single-crystal MgO(001) substrate of 0.5 mm thickness. Its physical properties are $T_c =$ 88 K, $J_c(T = 77\text{ K}) = 2.6\text{ MA/cm}^2$. Measurements were performed in the Ka-band using the $HE_{12\ 1\ 1}$ mode [50]. The authors found an improvement in film properties, i.e. decreasing $R_S(T)$, for a number of the films of different thicknesses a year

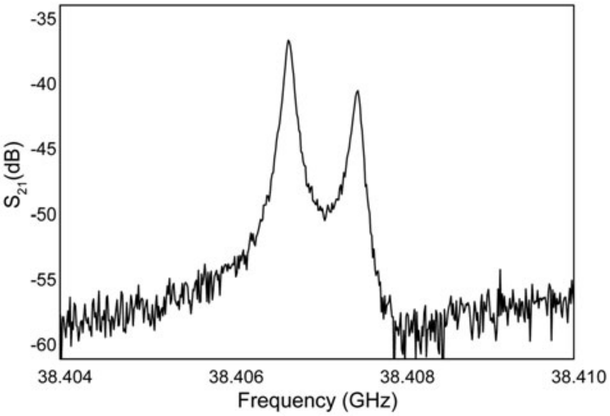


Fig. 5. Typical frequency response of WGM resonator with HTS film(s).

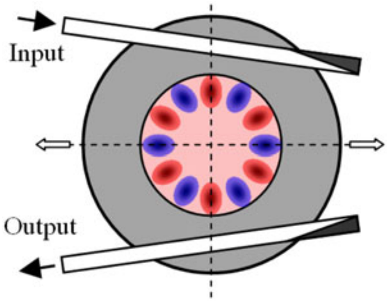


Fig. 6. WGM resonator and feeder dielectric waveguides with controlling coupling.

after their synthesis. The effect was explained by decreasing oxygen in slightly overdoped samples [51]. By comparing the characteristics of the three resonators considered above provided in Table 1 (data are given for $f = 35$ GHz), it can be concluded that a disc resonator is most suitable for precision measurements of surface resistance. At the same time, a hemispherical resonator is most suitable for precise individual measurements of films at low temperatures and a conical resonator can be used for test measurements at $T = 77$ K.

2) SMALL SAMPLES OF UNCONVENTIONAL SUPERCONDUCTORS

For a physical study of unusual superconductors of small dimensions, a disc WGM resonator with a radial slot was recently proposed and applied [40, 52]. The superconducting sample under study is positioned in the slot (Fig. 4). Such a resonator is particularly promising for studying new unusual superconductors with a critical temperature T_c below the critical temperature T_c^{HTS} of copper HTS films used as a CEP. It was applied to study pnictide $Ba(Fe_{1-x}Co_x)_2As_2$ [40] and $BaFe_{1.9}Ni_{0.1}As_2$ [52] single crystals. This approach makes it possible in principle to study the anisotropy of the impedance properties of superconducting single crystals. Here the problem is the significant level of radiation losses.

Precision measurements of the active and reactive components of in-plane MW surface impedance (Fig. 8) were performed in single crystals of the optimally doped Fe-based superconductor $Ba(Fe_{1-x}Co_x)_2As_2$ ($x = 0.074$, $T_c = 22.8$ K). Measurements in an mm wavelength range (Ka-band, 35–40 GHz) were performed using WGM with $YBa_2Cu_2O_7$ superconducting ($T_c = 90$ K) CEP. The temperature variation of the London penetration depth is best described by a power-law function, $\Delta\lambda(T) \sim T^n$, $n = 2.8$, in reasonable agreement with radiofrequency measurements on crystals of the same batch. This power-law dependence is characteristic of a nodeless superconducting gap in the extended *s*-wave pairing scenario with a strong pair-breaking scattering. The temperature-dependent quasi-particle scattering rate was analyzed in a two-fluid model, assuming the validity of the Drude description of conductivity and generalized expression for the scattering rate [53].

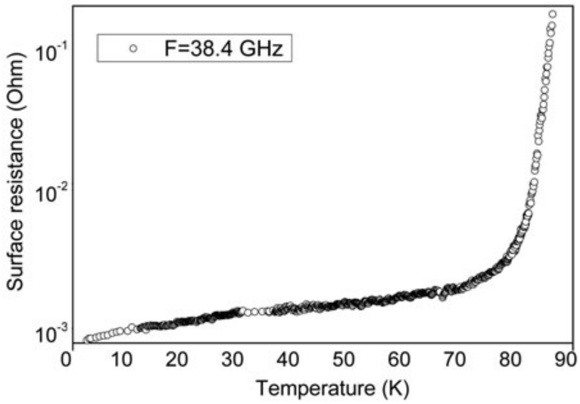


Fig. 7. RS(T) as a function of temperature for epitaxial $YBa_2Cu_3O_{7-\delta}$ film.

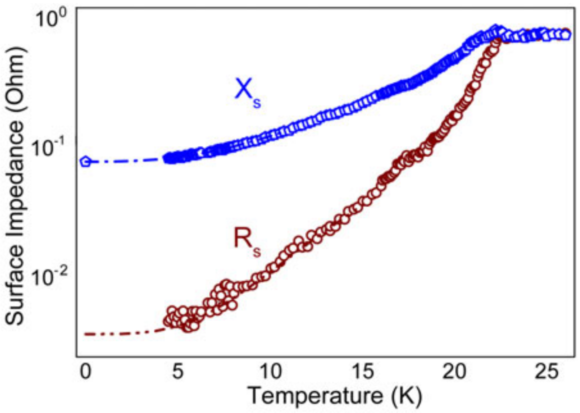


Fig. 8. Temperature dependence of surface resistance and surface reactance of single crystal $Ba(Fe_{1-x}Co_x)_2As_2$.

B) MW characterization of small volumes of lossy dielectric liquids

Biophysicians and medical researchers are also interested in finding appropriate approaches for measuring properties of condensed matter from the point of view biology and medicine. However, they need to measure dielectric liquids. The distinctive feature of the substances in contrast to the materials considered above and described in part (A) is a high level of MW losses, which makes it difficult to study and monitor these substances. Despite the difference in MW losses and the need to design the appropriate measurement procedures for substances with very high losses, it is also possible to develop measurement techniques based on high-*Q* resonators of the same type, namely WGM resonators. This aspect is based on the fact that the WGM resonators, because of their quasi-optical nature, are flexible in varying their shape and in the disturbance of the field by the sample under test to the extent necessary to achieve the required accuracy and sensitivity of measurements.

The resonator response measured in the form of the *Q*-factor and frequency *f* changes when a liquid with large losses, i.e. with $\tan\delta \cong 1$ (or even >1), is introduced into the resonator, and becomes a function of both parts of the complex permittivity ε. In this case, $Q = Q(\varepsilon',\varepsilon'')$ and $f = f(\varepsilon',\varepsilon'')$. Therefore, solving the inverse electrodynamic problem, i.e. a problem of finding $\varepsilon = \varepsilon' - i\varepsilon''$ using the measured *Q* and *f*, becomes a difficult task even with small perturbation of the resonator. In principle, permittivity of the lossy liquid can be found if the electrodynamic problem of a WGM resonator with the liquid is solved analytically.

However, it is not easy to find a solution even for the simplest case of the radially two-layered resonator with CEP [54].

1) RADIALLY TWO-LAYERED RESONATOR WITH CEP

The initial efforts of the authors and their colleagues were focused on studying the electrodynamic peculiarities of radially two-layered WGM resonators with liquid (Fig. 9). It was shown experimentally that when the resonator was filled with water and alcohol, a number of unusual features were observed. The resonator characteristics show anomalous behavior relative to the characteristics of the resonator perturbed by conductors or dielectrics with small loss; see, e.g. [22]:

- The *Q*-factor of the Teflon resonator with water is higher than that with alcohol, although tanδ of water is higher than tanδ in alcohol;
- A frequency shift Δf of the sapphire resonator with water has the opposite sign in comparison with the resonator with alcohol;
- A frequency shift Δf for water depending on a diameter of the radial slot is a non-monotonic function for both resonators.

However, the above-mentioned anomalies are explained by peculiarities of MW field penetration into lossy substance. Realization of the two-layered WGM resonator for permittivity measurements of lossy liquids encounters certain difficulties: (i) CEP decreases the *Q*-factor, which reduces the sensitivity and accuracy of the measurements and (ii) designing the resonator as the MW sensor is a complex task with respect to accurately determining the resonator dimensions, which are necessary for solving the inverse electrodynamic problem. The search for a solution to this challenge for the Ka-band WGM sapphire resonator is under way.

2) RESONATOR WITH MICROFLUIDIC CHANNEL

A consistent solution of the problem of finding a complex permittivity of small volumes of liquids (from microliters to nanoliters) was achieved in [42, 55] using a sapphire WGM resonator with a microfluidic channel located outside the sapphire disc (Fig. 10). This advanced approach was developed using experimental knowledge obtained during a study of the resonator with a capillary filled with a lossy dielectric liquid [56].

The dimensions of the channel and its position in a plastic layer can be measured with a degree of accuracy. More accurate data on the diameter of the channel and its position were obtained by a fitting procedure of the experimental and calculated data for a channel filled with water. This is important in order to increase the accuracy of the permittivity measurements.

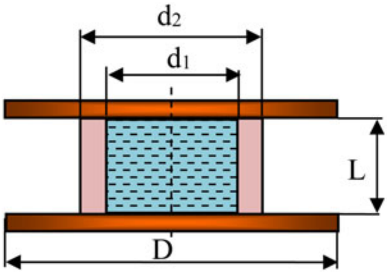


Fig. 9. Radially two-layer WGM resonator with liquid under test.

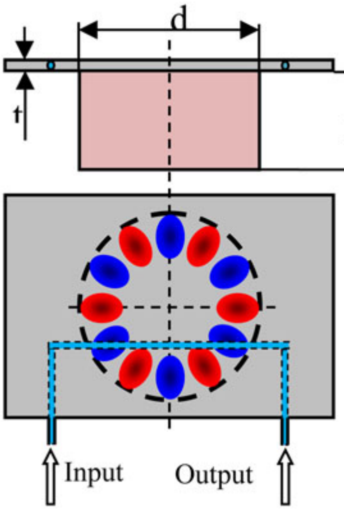


Fig. 10. Sapphire WGM resonator with microfluidic channel filled with liquid.

Another important step in solving the inverse electrodynamic problem is the development of a special 2D-nomogram [57], which allows a complex permittivity to be found for the measured resonator *Q*-factor and resonance frequency. Figure 11 shows the measured permittivity of the aqueous solution as a function of the concentration of cytochrome c. Measurement accuracy was $\delta\varepsilon'/\varepsilon' = 1.4\%$ and $\delta\varepsilon''/\varepsilon'' = 0.7\%$.

In the next section, we show that high-quality WGM resonators are important elements for developing advanced MW oscillators, which can also be used as master oscillators on satellite platforms.

C) Low-phase noise oscillators

WGM resonators represent a key element in achieving ultra-low phase noise in MW oscillators. This is determined by two factors. The first factor is the localization of the electromagnetic energy of waves inside the low-loss dielectric material resulting in high *Q*-factor resonators, which allow fluctuations to be suppressed down to several orders of magnitude. For single-crystal sapphire resonators, the *Q*-factor is found to be larger than 10^9 [58] at liquid helium temperature and

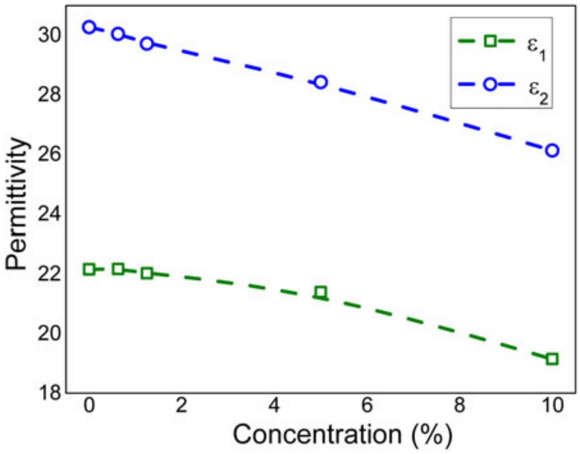


Fig. 11. Complex permittivity of aqueous solution of cytochrome C versus cytochrome concentration.

frequencies around 10 GHz because of its low tanδ. This is due to the fact that tanδ of sapphire strictly decreases with decreasing temperature in proportion to T^5 [59]. Such low-noise oscillators enable a great many unique studies and applications. Examples of such applications are low-noise MW oscillators developed with the aim of detecting gravitational waves [60], frequency-temperature compensated WGM oscillators [61], development of a laser-cooled cesium fountain clock to observe the quantum projection noise in atomic fountain clocks [62] as well as local oscillators for satellite platforms [63]. The latter represent the master oscillators in order to transform any frequency signals to the lower or upper frequency range due to mixing process, so that they are useful in all other frequency ranges in order to analyze and transform the data received by MW satellite systems.

The oscillator can be designed in a series or parallel feedback configuration (Fig. 12). The feedback oscillators are more often used and contain a WGM resonator, ultra-low pass filter to start the oscillator only in WGM high-quality mode, amplifier and phase shifter connected in the MW circuit for the adjustment of the 2π phase around the oscillator loop to meet the oscillation condition. The resonator has a broad spectrum containing a high density of WGM high-Q-factor modes as well as low-Q-factor modes due to the surrounding housing. Therefore overlapping of the modes has to be prevented by careful design of the WGM oscillator to use the full potential of the WGM. In addition, losses at any interfaces between the resonator, filter and coupling waveguides have to be minimized and residual losses have to be compensated using a low-noise amplifier. It should be noted that the gain coefficient of the amplifier has to be slightly above the losses. Also, the 1 dB working point followed by the linear amplification range would be the best choice for an ultra-low noise oscillator design. The basic phase noise behavior of the oscillator can be described using a simple Leeson model [64]:

$$L_{osc} = 10 \cdot \log\left[1 + \frac{f_o^2}{4Q_L^2 f_m^2}\right] + 10 \cdot \log\left[\frac{\alpha}{f_m} + \frac{GFkT}{P}\right]. \quad (5)$$

The second term in equation (5) represents the amplifier noise consisting of white noise determined by the amplifier gain G and its noise figure F, physical temperature T, and output power P. In addition, there is $1/f$ noise leading to a fluctuation amplitude α/f_m at a frequency distance $\pm f_m$ from the carrier frequency f_o. The first term in equation (5) represents the resonator noise amplification factor, which is 3 dB for $f_m = \frac{1}{2}\,\Delta f_{1/2}$ $(\Delta f_{1/2} = f_o/Q_L)$ and increases strongly for lower offset frequencies. According to equation (5), the oscillator phase noise exhibits $1/f_m^3$ dependence in a certain range of offset frequencies. This noise decreases strongly upon increasing the loaded quality factor Q_L of the resonator. The latter is strongly dependent on the MW power. The higher the power of the amplifier the better is the loaded quality factor.

Figure 13 shows the phase noise measurement results for the amplifier (curve 1) and 23 GHz oscillator (curve 2). The amplifier phase noise exhibits almost ideal $1/f$ dependence without a generation-recombination component with an absolute value of −140 dBc/Hz at a frequency offset of 1 kHz, which is nearly independent of the value of the voltage applied to the transistor. Curve 2 in the figure shows the level of the measured oscillator phase noise at a frequency offset of 1 kHz with an absolute value of −118 dBc/Hz, which is superior to any commercial K-band oscillators.

The drawbacks of WGMs are the relatively large mode density, their dual-mode character and the high-temperature coefficient of the resonant frequency of about 40 ppm/K at $T = 77$ K. However, for $m \geq 7$ the loss contribution of the metallic housing becomes negligible and Q values in the 10^7 range become possible at temperatures of 50–80 K, which are accessible with low-power cryocoolers [63]. In addition, a number of solutions to the challenges have been suggested [65]. To obtain frequency–temperature compensation a new dual-mode resonator technique is proposed using high-quality oscillators with orthogonally polarized WGMs in the same resonator [66]. A unique spectral performance has been demonstrated making WGM oscillators suitable for a wide range of scientific applications and high-precision tests required by modern physics [58].

Decreasing temperature results in a reduction of phase noise. Our results demonstrate the superior characteristic of phase noise in cryogenic oscillators at $T = 77$ K in comparison with conventional oscillators. For conventional oscillators, the up-conversion factor, which is important for phase modulation in modern telecommunication systems, is about 3 MHz/V for an offset frequency of 1 kHz. The up-conversion factor [67] in our oscillators is about 50 kHz/V for the same offset frequency, which results in an oscillator phase noise of only −118 dBc/Hz [63]. This value is superior to quartz-stabilized oscillators at 1 kHz frequency offset. The main trend in new

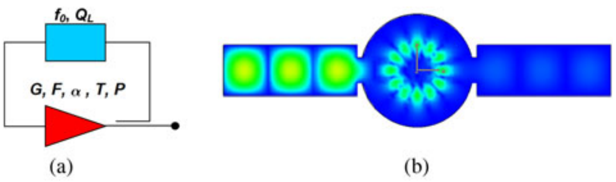


Fig. 12. (a) Oscillator circuit with resonator (square), and transistor amplifier (triangle), f_o is the resonance frequency, QL is the loaded Q-factor, G is the amplifier gain, P is the output power of the amplifier, T is the temperature, F is the noise figure, α is the flicker noise constant of the amplifier. (b) Calculated distribution of electric field amplitude for a WGM resonator coupled by waveguides.

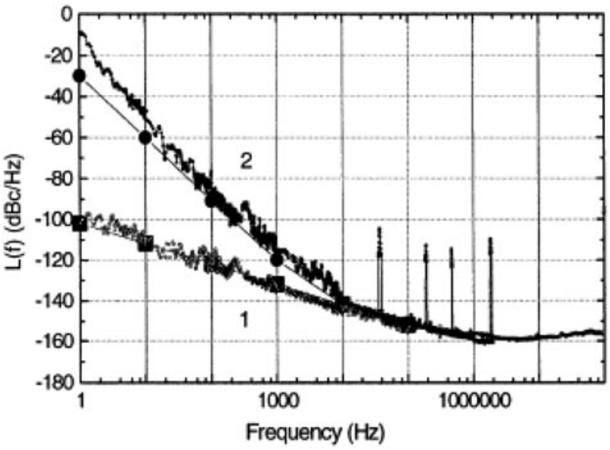


Fig. 13. Measured phase noise: (1) of the amplifier and (2) of the oscillator. Squares: $1/f$ fit to the amplifier noise. Circles: oscillator phase noise calculated from the fit to the amplifier phase noise according to the Leeson formula.

communication systems is a movement toward miniaturization, a higher-frequency range and higher power. The higher the frequency, the stronger is the requirement for the phase noise level of the local oscillator to achieve a reduced rate of bit errors. The phase noise level depends strongly on output power and can be considerably decreased by increasing the power of the active element – transistor amplifier. Today GaN and III-nitrides are the most promising candidates for high-power low-noise MW generation due to their superior physical properties in comparison with other materials. In this respect, a combination of GaN- and III-nitride-based amplifiers with high-quality-factor WGM resonators offers a unique technique for oscillator development for a number of scientific applications.

According to equation (5), the lowest possible oscillator phase noise ($Q_L \rightarrow \infty$) is determined by the phase noise of the amplifier, which can be minimized using high-power GaN-based amplifiers [68]. In order to achieve an oscillator phase noise close to that of the amplifier for frequency offsets of one kilohertz, extremely high resonator quality factors are required. Employing the above-mentioned 3 dB criterion according to equation (5), for a frequency offset of $f_m = 1$ kHz, the required loaded quality factor is 1.1×10^7. In the case of high-purity sapphire as the resonator material, WGM resonances allow the highest unloaded quality factors above liquid helium temperature, which are close to those of superconducting niobium cavities.

D) Solid-state maser oscillators

Some years ago, a new type of stable cryogenic sapphire oscillator was proposed [69] and developed [70, 71]. It exhibits several important features: it presents a solid-state maser device, its output is orders of magnitude higher than that of hydrogen maser oscillators and its low-noise amplification combined with high Q-factor provides the condition for exceptionally low phase noise.

The fundamental aim of quantum systems applied in maser devices is to obtain an inversion of energy-level populations [72]. Achieving the inverted, i.e. active state, is a necessary condition of net MW coherent emission. In the traditional approach, more than two energy levels are used to apply, mainly, three- or four-level pumping. At the same time, a magnetic field is applied in traditional solid-state masers in order to obtain a suitable spectrum of electron paramagnetic resonance (EPR). Using the masing effect, a number of extremely low-noise amplifiers, including some in the mm-wave range, were developed [73].

In the above-mentioned new type of maser oscillator [69–71], the masing effect results from the coincidence in frequency of the zero-field EPR of Fe^{+3} ions with a very high Q-factor ($>10^9$) WGM at 12.04 GHz. The obtained relatively high-output power ($\sim$2.5 nW) and low-noise amplification lead to the Schawlow–Townes frequency stability limit of the order of $10^{-16}\tau^{-1/2}$, where τ is the measurement integration time [74].

The principle of the Fe^{+3} WGM maser oscillator, the energy-level diagram for Fe^{+3} in sapphire at zero applied magnetic field and the maser signal are shown in Figs 14 and 15, respectively [70].

Here some background related to the idea of developing a solid-state maser oscillator using a WGM resonator should be mentioned. In 1989, two of the authors of this review, studying the properties of sapphire WGM resonators in the mm-wavelength range, expressed the idea of creating a solid-state maser oscillator, where the maser (active) crystal is a WGM resonator [75]. The authors took into account such peculiarities of WGM resonators as high Q-factor, chance of operation in mm-wave range at both oscillation and pump frequencies and insensitivity of dielectric crystal properties to static magnetic field (apart from the effect of dc magnetic field on the EPR spectrum). The authors [75] were pleased to learn that the same idea with an appropriate technical solution has been patented [69] and implemented [70, 71]. It should be noted that the authors [75] pointed to a ruby single crystal (Al_2O_3:Cr^{3+}) as a maser medium, in which oscillation frequency is controlled by the static magnetic field in order to apply a three- or four energy-level pump. The high stability of such a field can be achieved by freezing the magnetic flux in a superconducting magnet of special design [73]. In [69], the active crystal with three Kramers doublets in zero magnetic field was proposed. In this case, the external magnetic field is not required. However, the maser oscillator can operate at a single frequency, determined by the nature of the material. For example, the authors [69–71] obtained oscillations at 12.04 GHz, which is determined by the frequency of quantum transition between the lowest Kramers doublets in the EPR spectrum of the Fe^{3+}ions in sapphire. In the future, if there should be a need to design the solid-state maser oscillators to achieve higher frequencies or by tuning the frequency, the ruby, which was widely used in the maser amplifiers, may be a promising crystal for the maser oscillators.

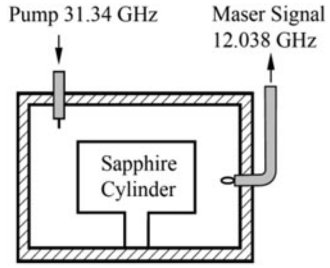


Fig. 14. Principle of the WGM maser oscillator.

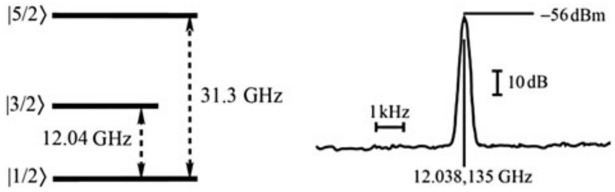


Fig. 15. (a) Energy-level diagram for Fe^{+3} in sapphire at zero magnetic field and (b) the unamplified maser signal as observed on a spectrum analyzer.

E) Auto-oscillatory system with REBs

In recent years, vacuum electronics technology has exhibited a trend toward the mm- and submm (THz)-wavelength range. The use of traditional approaches for designing and constructing these electronic devices encounters considerable difficulties related, in particular, to the small geometric dimensions of the main elements that generate and stabilize electromagnetic oscillations. The solution of this problem leads to the use of oversized (relative to wavelength) electrodynamic structures operating in multimodal regimes. Stable electromagnetic

Table 2. Eigenfrequencies and Q-factor of WGM resonator.

Mode	$TM_{36\ 1\ 0}$	$HE_{36\ 1\ 1}$	$HE_{36\ 1\ 2}$
Frequency (GHz)	34.9916	36.8385	42.0046
Q-factor	4870	6035	6056

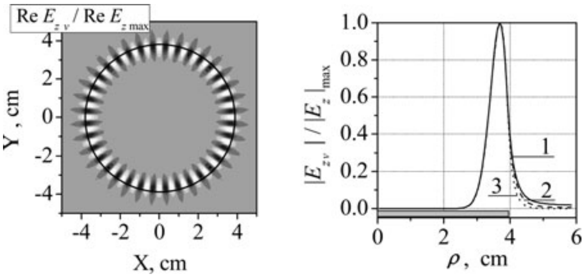


Fig. 16. Distribution of $E_{z\nu}$ components of $TM_{36\ 1\ 0}$ (1), $HE_{36\ 1\ 1}$ (2), and $HE_{36\ 1\ 2}$ (3) modes in QDR ($\nu = 1$ for $\rho \le \rho_0$; $\nu = 2$ for $\rho > \rho_0$).

oscillations are closely related to the excitation and selection of high-order modes in these structures.

The possibility of exciting weakly decaying WGMs in the WGM resonator gives rise to hopes of using them in mm and submm vacuum electronic devices [76–78], where the above-mentioned technological problems can be solved. The output power of traditional radiation sources drops sharply in the submm range [79]. Therefore, a need arises for high-energy oscillators excited by electron beams. It should be noted that the use of oversized structures with oscillations excited by high-current REBs also eliminates the problem of electric breakdown [76–78]. The proposed source design is based on the use of the electrodynamic properties of the resonator [9, 11], which serves as the main element in the auto-oscillatory system [78].

The authors [78] used a Teflon resonator with a radius of $\rho_0 = 3.9$ cm and a length of $L = 0.9$ cm. Table 2 gives the values of the eigenfrequencies f_{msl} and Q-factors for the resonator with HE modes where the azimuth n and radial s indices are equal to 36 and 1, respectively, and the axial l index equals 0, 1, or 2. The resonator dimensions and operating modes were determined by the desired frequency range of the auto-oscillatory system described below. The mode type was determined by the resonator excitation.

Figure 16 shows the field distribution of the HE modes of the WGM resonator. The fields of weakly decaying WGMs are concentrated inside the dielectric close to the cylindrical surface of the resonator. In order to excite oscillations, it is necessary to introduce a source of alternating energy into the evanescent field of the eigenmode with a fluctuation frequency equal to f_{nsl}. The use of an electron beam that is parallel to the side surface of the resonator as an excitation allows the HE modes to be excited [76, 77]. In order to select modes with a particular azimuthal index n, it is necessary to use the appropriate azimuthally periodic (AP) electron beam. Making allowance for the phase synchronism, the excitation of the above-mentioned WGMs requires an electron beam consisting of $n = 36$ streams with an angular distance between them along the azimuthal coordinate of $360°/n$.

Schematic diagrams of the auto-oscillatory system and the experimental setup are shown in Fig. 17 [77]. The oscillations in the resonator are excited as a result of the resonant interaction between the HE_{nsl} modes and the transient and/or Cherenkov radiation from electrons in the AP electron beam propagating near the cylindrical surface [76, 77] at the resonator frequencies (Table 2). The HE_{nsl} mode energy is converted into radiation when its field excites the slit radiator (or a system of such radiators as elements of a phased array) situated at the maximum of single field variation (maxima of unipolar variations) with respect to both radial and azimuth coordinates.

The proposed auto-oscillatory system was experimentally investigated on a high-current linear electron accelerator "Temp A" (Fig. 17), the parameters of which are listed in [78]. The accelerator generated a pulse of REB with energy of 300 keV and a pulse duration of 3 μs at half-maximum power level. The AP electron beam structure was formed by transmitting this tubular REB through a perforated resonator front endplate, which yielded 36 phase-synchronized electron streams. The radius of the AP electron beam was 4.1 cm and the diameter of electron stream was 0.4 cm. The AP REB propagating near the cylindrical surface of the Teflon resonator excited the $HE_{36\ 1\ l}$ eigenmode ($0 \le l \le 2$) with a frequency within 35–42 GHz.

The electromagnetic radiation output of the system under consideration was measured by a Ka-band detector. The typical waveforms of: (a) REB current pulses, (b) voltage of magnetically insulated diode, and (c) normalized power (P/P_{max}) of the electromagnetic radiation output are shown in Fig. 18. The durations of these pulses were ~3 μs and the amplitudes of current and voltage were 2.2 and 300 kV, respectively.

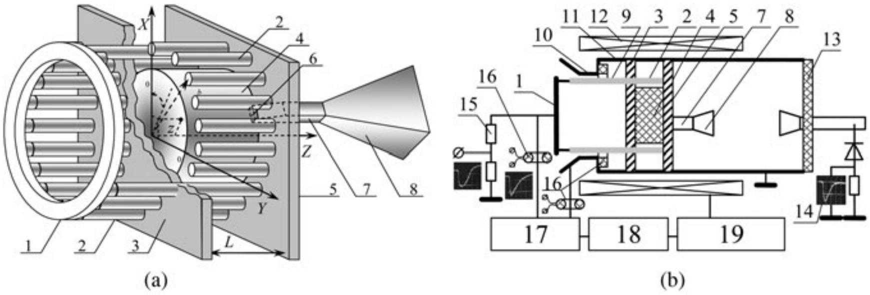


Fig. 17. Schematic diagrams of (a) auto-oscillatory system based on a QDR with WGMs and (b) experimental setup: (1) cathode; (2) azimuthal-periodic electron beam; (3) perforated anode (QDR front endplate); (4) QDR; (5) electron collector (QDR rear endplate); (6) slit; (7) waveguide; (8) horn antenna; (9) tubular REB; (10) anode; (11) liner; (12) solenoid; (13) dielectric window; (14) detector; (15) voltage divider; (16) current probe (Rogowsky coil); (17) pulsed voltage generator; (18) switch-on and control system; (19) system of external magnetic field formation.

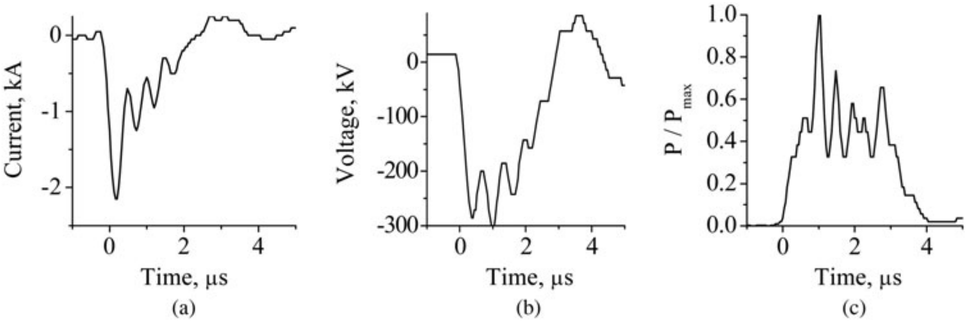


Fig. 18. Typical waveforms of: (a) REB current, (b) high-current diode voltage, and (c) normalized power ($P/P_{\max}$) of microwave radiation.

IV. CONCLUSION

An overview is given of the results of studying WGM resonators with the aim of attracting the attention of the broad scientific community to the unique possibilities of utilizing resonators in physics and technology in the mm- and submm-wavelength range. Advanced approaches mainly developed on the basis of the authors' studies are presented. An overview of the theoretical results is given without mathematical expressions that are cumbersome and are, in any case, contained in the cited references. The authors emphasized that the analytical solutions are of importance themselves and also for testing different MW program products.

The unique characteristics of sapphire resonators, such as an extremely high-quality factor and the stability of the frequency spectrum, as well as the flexibility to control the interaction of the WGM fields with the test substances enables the physical properties of materials to be measured with very different values of losses with high accuracy. Advanced approaches are developed to measure extremely low values of surface impedance of unusual superconductors of two shapes (large-area films and small-sized single crystals), on the one hand, and the complex permittivity of dielectric liquids and small volumes with a large value of loss tangent, on the other.

WGM resonators also allow active devices to be developed, among which the best known examples are represented by transistor-based low-phase noise oscillators and high-stability solid-state masers. In this respect, the devices developed by utilizing Ka-band transistor amplifiers show remarkable performance. The WGM-based resonator devices offer an exciting potential and a lot of advantages and unique opportunities ranging from fundamental research and development to a number of useful applications, including oscillators for future MW communication systems.

The first results of an experimental study of a self-oscillating system based on the interaction of electron beams with WGM fields are demonstrated, which indicate the prospects and reliability of a new approach for the generation of high-intensity mm and submm waves.

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