Quasioptical Sapphire Resonators in the Form of a Truncated Cone

Alexander A. Barannik, Sergey A. Bunyaev, Nickolay T. Cherpak, *Senior Member, IEEE*, and Svetlana A. Vitusevich

***Abstract*—This paper reports on a detailed experimental study of quasioptical dielectric resonators (QDRs) designed in the form of a truncated cone and excited on whispering-gallery modes. One aim of this paper is to study of the eigenfrequency spectrum and quality factors of single-crystal sapphire resonators. A second aim is to show the applicability of the resonator technique not only in optical but also in the millimeter-wave range, in particular, for studying the surface resistance (R_s) of high-temperature superconducting films. The measured frequencies of QDR as a function of the wedge angle of the cone resonator are in a good agreement with those frequencies simulated using the CST Microwave Studio 2006 program. Additionally, electrodynamic characteristics of the cone resonator and hemispherical dielectric resonator with conducting endplate are compared.**

***Index Terms*—Dielectric resonators, millimeter-wave measurements, Q factor, quasioptical resonators, superconducting films.**

I. Introduction

QUASIOPTICAL dielectric resonators excited on whispering-gallery modes (WGM) are usually fabricated and studied in the form of a cylinder (see, for example, [1]–[3]). The WGM waves propagate by quasioptical reflection along the circumference of the cylinder; therefore, these resonators are called quasioptical (QDR) or whispering gallery resonators (WGRs). Recently, we demonstrated that such cylindrical resonators with conducting endplates can be used to measure the surface resistance R_s of thin high-temperature superconducting (HTS) films [4], [5]. The advantages of this method are the increased sensitivity for a determination of small resistance R_s values in the millimeter wavelength range (the minimum value of R_s, which can be determined by this method, is about 4×10^{-5} Ohm for the Ka-band frequency range [5]) and the possibility of measuring their absolute values. In this resonator geometry, the calibration procedure (including additional measurements with the use of metal endplates of known R_s value) is not necessary because the electromagnetic-field structure in the resonators is determined directly from an analytical solution of the Maxwell equations. However, such an approach also has a disadvantage since the surface resistance obtained is related to both HTS films, which are the endplates of such a resonator. The determination of the individual R_s value requires carrying out a special "round-robin" procedure [6], demanding three measurement thermocycles with three pairs of three different films, which is a time- and cost-consuming procedure. In order to solve this problem, a resonator with a special geometry has to be developed, allowing a single conducting surface of the endplate to be studied and an analytical solution of the electromagnetic-field distribution to be found. It should be noted that high sensitivity as well as accuracy (due to first principle Rs measurements) are important characteristics, even in the millimeter wavelength range, for the investigation of fundamental superconductivity at very low temperatures, below 4.2 °K.

One possible technique for the single endplate resistance study is offered by the dielectric hemisphere resonator with a metal plane [7]. It has been shown experimentally that in this resonator geometry, the WGMs running along a hemisphere base can be excited [8]. Unfortunately, the electrodynamic problem of this kind of resonator considering the anisotropy of the dielectric material and the finite impedance of the metal endplate still has not been solved. Additionally, manufacturing high-Q hemispherical quasioptical resonators from a single-crystal leucosapphire is a rather complicated and labor-consuming technique.

As an alternative approach, we proposed QDR in the form of a cone. As we showed earlier, such a resonator also allows exciting WGM waves along a cone base, similar to the hemispherical resonator, but the cone resonator can be more easily fabricated. Such a resonator with a wedged-shaped edge and small height was used as an optical microdisc [9].

The first microwave experimental results of eigenfrequencies, the quality factors, and electric-field structure as a function of angle in the angle range from 0° to 35° were obtained for a resonator that was fabricated from an easy-to-machine material—Teflon. They demonstrate a strong dependence of the aforementioned parameters from the angle. These investigations were supplemented by the results of studies of cone and biconical resonators and the comparison with those of the hemisphere resonator [12]. It was shown that the simple single wedge angle cone resonator is the optimal choice due to smaller radiation losses and the simplest fabrication.

Recently, information has appeared that in very thin disc resonators with a wedged-shaped edge, the WGMs are excited in an optical wavelength range with a Q value exceeding those found for the cylindrical discs of the same diameter [13] due to isolation of the mode from the disc perimeter and thereby reducing scattering loss. However, this effect has not been found in the millimeter-wave range [14] despite higher accuracy of the QDR

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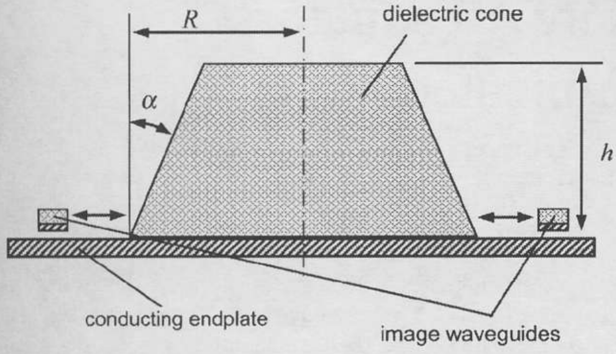

Fig. 1. Cone quasioptical dielectric resonator with conducting endplate.

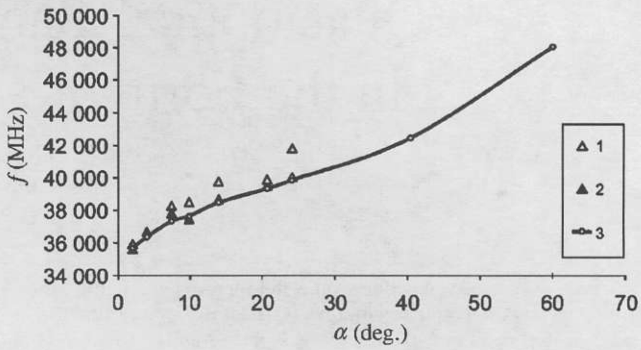

Fig. 2. Eigenfrequency as a function of α for a sapphire cone resonator without 1) and with 2) a copper-conducting endplate. The continuous curve was calculated and obtained using the CST Microwave Studio 2006 3).

characteristics determination in the microwave frequency range in comparison with the optical range. The accuracy can be considerably increased by using high-quality sapphire material. The motivation for this work is the investigation of cone resonators made from a high-Q sapphire dielectric material. This is important for the fundamental characteristics study of these new kinds of resonators and for the development of high sensitivity sensors for the measurement of the properties of HTS thin films. Therefore, we experimentally studied the microwave properties of cone resonators made of sapphire and compared them with the results of our simulations. Additionally, we demonstrated applicability of the cone resonators technique for the determination of the R_s value of thin YBCO films.

This paper is organized as follows. Section II describes experimental details. Section III presents the experimental results of the investigation of sapphire cone resonators and calculation results for them together with a discussion. Section IV describes the main conclusions.

II. Experimental Details

Sapphire resonators were fabricated in the form of a truncated cone (Fig. 1) because the microwave field is concentrated nearly on the bottom of a cone (even at a very small angle $\alpha = 2°$ [10], [11]). The field at the top is negligibly small and the cone resonator can be reduced to a truncated shape. The height of the cone resonators H was chosen to be equal to the radius of the cone bottom base R in order to provide a close analogy to the hemispherical resonator.

An azimuthal number n of mode and, hence, a diameter of the cone bottom base is optimized, taking into account the tradeoff between the increasing Q-factor and reducing mode spectral density depending on n by analogy with the cylindrical disk resonator. The radius of the cone basis of the resonator manufactured from the single-crystal sapphire was chosen to be the same, 7.4 mm, as for the case of the cylindrical QDR, which we have previously investigated (see, for example, [4] and [5]). An optical c-axis of the crystal was directed along the longitudinal axis of the cone. The wedge angle (α) of the cone was mechanically changed step by step from 0 to 24.1°. The measurements were performed in a frequency range from 35 to 45 GHz. The endplates were made from copper ($R_s = 0.06\ \Omega$). The resonators were excited using rectangular dielectric waveguides that were metal-coated on one side. The waveguides were made of the same material as for the excited resonator and oriented in a way that HE modes could be excited in the cylindrical resonator ($\alpha = 0°$). The quality factor Q was determined from the resonance peak corresponding to WGM wave under weak coupling conditions. The electric-field distribution for the identification of modes in the resonator was measured by the electromagnetic-field perturbation method with a metal test probe.

III. Results and Discussion

The inverse value of the resonator quality factor as a function of α can be described using the following simple expression [4]:

$$Q^{-1} = k\text{tg}\delta + A_s R_s + Q_{\text{rad}}^{-1} \tag{1}$$

where k is a constant close to unity, $\tan\delta$ is the loss tangent of the dielectric material, $A_s = \Gamma^{-1}$ is the coefficient of inclusion of the conducting endplate, which is expressed by the frequently used geometric factor Γ, R_s is the surface resistance of the endplate metal, and Q_{rad} is the radiation quality factor.

As α grows, the unloaded Q of the resonator without endplate ($A_s = 0$) can only decrease due to increased radiation losses. At the same time, the Q value of the resonator with the endplate can decrease as a result of the increase of two factors: 1) due to increased radiation losses and 2) conductivity loss in a metal endplate. The dependencies of A_s and Q_{rad} dependencies on the angle α for the Teflon cone resonator were presented in [11].

The characteristics of the sapphire resonator: 1) with normally conducting endplate and without it at room temperature and 2) with high-Tc $YBa_2CuO_{7-\delta}$ film as a test endplate in a temperature interval of 77 to 90 °K were studied. Fig. 2 shows the measurement results of the $\text{HE}_{14\ 1\ 1}$ mode resonant frequency dependence on α, where $\text{n} = 14$ is the azimuthal index, $\text{m} = 1$ is the number of field variations along the radius of the cone base, and $\text{s} = 1$ is a number of the field variations along the cone axis.

It can be seen that the eigenfrequencies of the resonator with and without the endplate increase when α gains (at $\text{n} = \text{const}$) as was revealed for the case of the Teflon resonator [11]. However, the dependence is not so strong as for the case of the Teflon resonator.

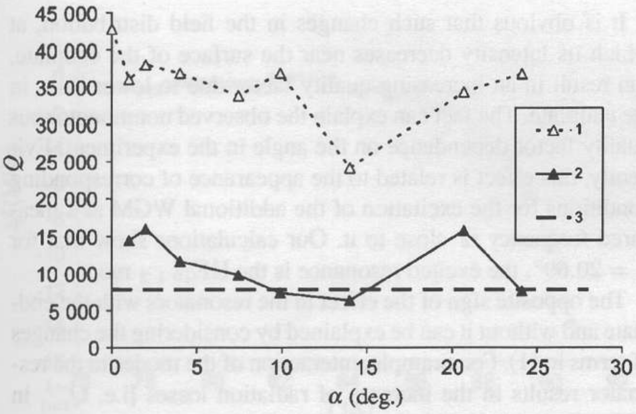

Fig. 3. Unloaded quality factor as a function of the angle of α for a sapphire cone resonator without 1) and with 2) a copper endplate. For comparison, the quality factor of the sapphire hemispherical resonator with the endplate is shown as a reference dashed line 3).

As can be seen from Fig. 2, the experimental and simulated data for the resonator with the endplate are in a good agreement. The results of the $HE_{14\,1\,1}$ mode quality-factor measurements for the cone sapphire resonator at different α are presented in Fig. 3.

Quality-factor measurements of cone resonators with and without the endplate show that the Q values for both resonators decrease nonmonotonous with an increase of α (also see the results of calculated field redistribution, corresponding to the oscillating part of this dependence, shown in Figs. 4 and 5). However, the change does not exceed 10% for the resonator without the endplate, which demonstrates a sufficiently weaker decrease of the radiation quality factor of the resonator in the range of measured values of angle α. The only exception is at the angle $\alpha = 13.97°$, where the Q factor of the resonator without the endplate decreases considerably. After that at the larger angles, Q increases again to reach values that are practically equal to those corresponding to very small angles. It should be noted that the reduction of the quality factor to $Q = 24000$ at the angle $\alpha = 13.97°$ is due to mode interaction with another mode. An accurate calculation of a field structure showed that studied mode $HE_{14\,1\,1}$ [Fig. 6(a)] at $\alpha = 13.97°$ interacts with the mode $HE_{10\,1\,2}$ [Fig. 6(b)], which has the same frequency. Redistribution of electromagnetic-field energy between modes leads to reducing the quality factor of the $HE_{14\,1\,1}$ mode.

Measured values of the quality factor $Q\ (< 4 \cdot 10^4)$ of the cone resonator without the endplate are lower than Q of the cylindrical and hemispherical ones $(\sim 4.5 \cdot 10^4)$ even at small angles α. The difference increases with temperature decreasing (for example, at cryogenic temperature T = 77 K, $Q = 2 \cdot 10^5$, and $5 \cdot 10^5$ for cone and cylindrical/hemispherical resonator, respectively). The results can be explained by an increased level of radiation loss in the cone resonator. Measured values of the quality factor Q of the resonator with the endplate depend more strongly on α compared to the case of the resonator without one. The value of Q already at $\alpha = 9.87°$ becomes lower than the quality factor of the hemispheric sapphire resonator with the endplate, where the radius of the base of the hemisphere and

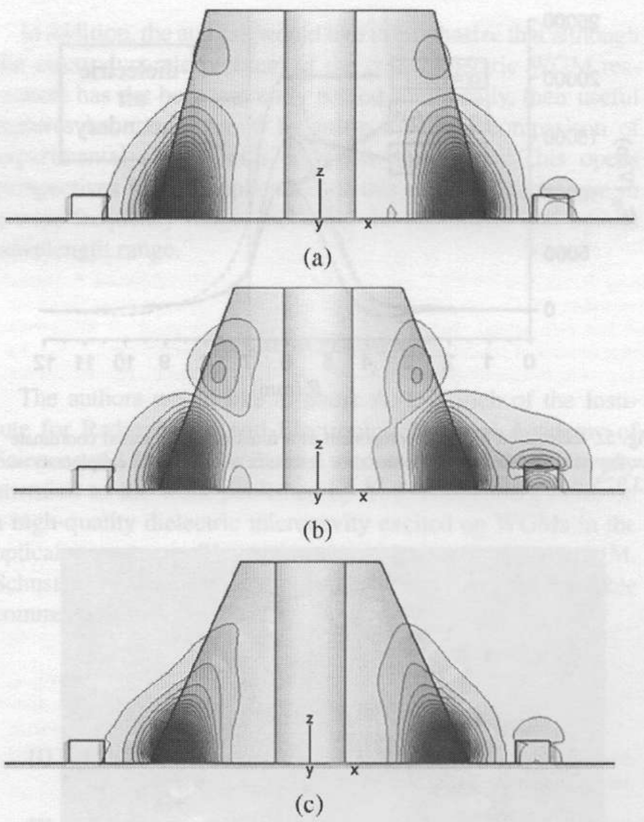

Fig. 4. Calculated field redistribution (E_z component) for three values α for a sapphire cone resonator with a copper endplate: (a) $\alpha = 13.97°$, (b) $\alpha = 20.69°$, and (c) $\alpha = 24.1°$.

cone is the same. The lower values of the quality factor correspond to the larger value of the coefficient A_s of the conductor at an angle of $\alpha \geq 9.87°$, assuming a small level of radiation loss.

Therefore, according to (1), in this case, the high sensitivity of R_s measurements can be obtained by using the cone resonator as the sensor for impedance measurements of conducting or superconducting materials. As can be seen in Fig. 3, the unusual changes of the quality factor are registered at angles $\alpha = 13.97°$ and $\alpha = 20.59°$. Obviously, with both "anomalies," the low quality factor at $\alpha = 13.97°$ for the resonator without the endplate and the high quality factor at $\alpha = 20.59°$ for the resonator with the endplate have the same nature.

This conclusion is supported by the results of the simulations of field distribution in the resonator with the endplate for angles $\alpha = 13.97°$, 20.59°, and 24.1° (Figs. 4 and 5).

Calculated results for the field redistribution in a longitudinal section of the cone for these three angles show also a trend towards forming an additional field variation along the cone surface (Fig. 4).

Fig. 5 shows the E_z field component as a function of the radial coordinate for three values of α for a sapphire cone resonator with a copper endplate $\alpha = 13.97°$, $\alpha = 20.69°$, and $\alpha = 24.1$ of the same mode $HE_{14\,1\,1}$. It should be noted that the angle dependence of the field is not monotonous because the field amplitude is minimal in the cone with $\alpha = 20.69°$ (which results in an increase of the quality factor). In fact, the quality

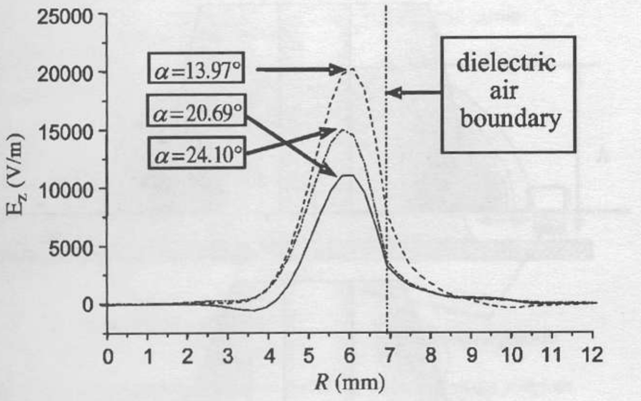

Fig. 5. Calculated E_z-field component as a function of the radial coordinate for three values of α for a sapphire cone resonator with a copper endplate: $\alpha = 13.97°$, $\alpha = 20.69°$, and $\alpha = 24.1°$.

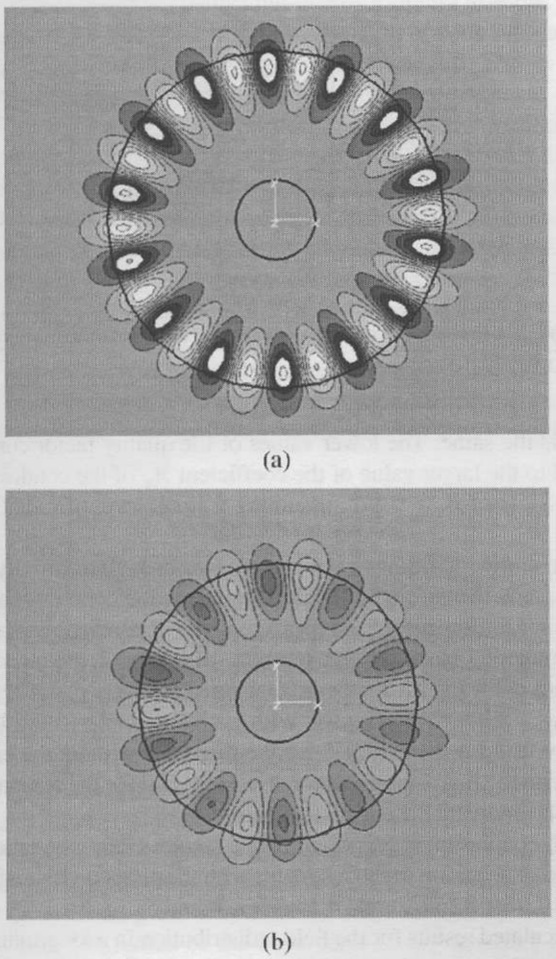

Fig. 6. Numerically calculated electric-field distribution in the XY-plane of the truncated cone resonator for different cross sections. (a) Mode $HE_{14\,1\,1}$ (the distance from the cone bottom base is 3 mm) and (b) mode $HE_{10\,1\,2}$ (the distance from the cone bottom base is 7.2 mm).

factor is unusually high for this angle (see Fig. 3). Besides, it can be seen in Fig. 5 that the pattern of the field distribution along the radius even changes qualitatively due to the appearance of a noticeable second variation of the field.

It is obvious that such changes in the field distribution, at which its intensity decreases near the surface of the endplate, can result in an increasing quality factor due to lower loses in the endplate. The fact can explain the observed nonmonotonous quality factor dependence on the angle in the experiment. Evidently, this effect is related to the appearance of corresponding conditions for the excitation of the additional WGM at a measured frequency or close to it. Our calculations show that for $\alpha = 20.69°$, the excited resonance is the $HE_{10\,1\,2}$ mode.

The opposite sign of the effect in the resonators with the endplate and without it can be explained by considering the changes of terms in (1). For example, interaction of the modes in the resonator results in the increase of radiation losses [i.e. $Q_{\rm rad}^{-1}$ in (1)], which, in turn, decreases the quality factor at some constant value of a loss ($k \tan\delta$) in the cone dielectric resonator without the endplate. The interaction of the modes in the resonator with the endplate cannot only cause increasing radiation loss, but also decreasing impedance loss in an endplate due to a change of the field distribution ($A_s R_s$). The aforementioned decrease may not only be comparable to the radiation losses, but can also exceed them.

The sapphire cone QDR with HTS film as an endplate was used to study the temperature dependence of the HTS thin-film microwave properties. The eigenfrequencies and unloaded quality factor were measured. The $YBa_2CuO_{7-\delta}$ thin film, which has a critical temperature of $T_c \cong 90$ K, was studied. The film of 600-nm thickness was synthesized on a single-crystal sapphire substrate of 0.5 mm in thickness. The temperature dependence of $\Delta f(T)$ for the resonator with the HTS film is shown in Fig. 7. The dependence can be used to analyze the film reactance properties. The measurements were carried out at an angle of the cone $\alpha = 13.97°$. Temperature dependence of the film surface resistance R_s is shown in Fig. 8, measured at $\alpha = 13.97°$. The value of a coefficient $A_s = 2.082 \times 10^{-3}\ \Omega^{-1}$ was obtained by (1) for the case of $Q_{\rm rad} \gg Q$ using a calibration procedure with a known resistance endplate made from copper with $R_s(\mathrm{T} = 300\ \mathrm{K}) = 60\ \mathrm{m}\Omega$. The resistance was measured using a cylindrical disk QDR [4]. A measured value of the resistance R_s is a little bit higher than the resistance of oxygen-free high-conductivity copper. The fact demonstrates that the copper CEP was slightly oxidized.

The measured value $R_s(\mathrm{T} = 78\ \mathrm{K})$ of the film of 600-nm thickness is equal to 33 mΩ with an accuracy of 1.7 mΩ (about 5%). The accuracy of the R_s measurement by using the cone resonator with one endplate (i.e., at the measurement of one HTS film), is approximately the same as the measurements of a cylindrical disc resonator with two endplates (i.e., at the measurement of the average value of two HTS films). On the other hand, the cylindrical disk-based technique needs two endplates that deteriorate the measurement accuracy since R_s, in this case, is estimated by averaging the values for two individual films.

IV. Conclusion

In summary, a new type of high-quality factor sapphire quasioptical resonator in the form of a truncated cone with conducting endplates and without them was designed and studied experimentally in the millimeter wavelength range. Eigenfrequencies and quality-factor values were obtained as a function

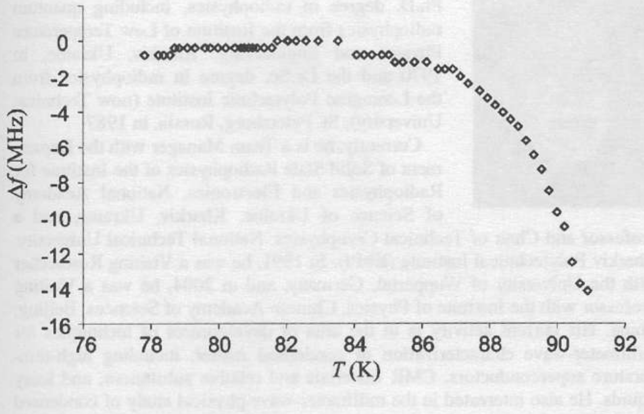

Fig. 7. Temperature dependence of $\Delta f(T)$ for the sapphire cone resonator with $YBa_2CuO_{7-\delta}$ film.

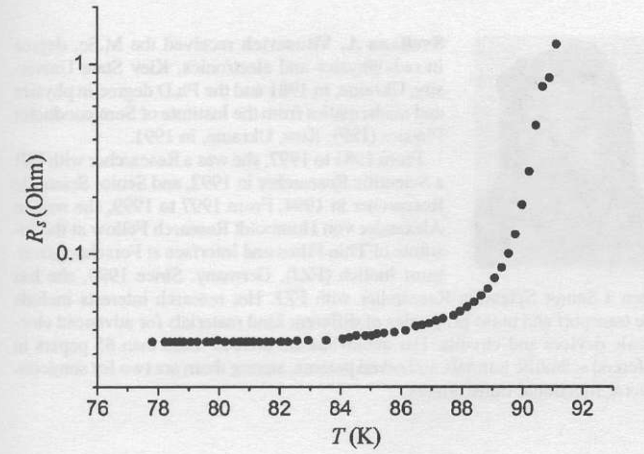

Fig. 8. Temperature dependence of $R_s(T)$ for the sapphire cone resonator with $YBa_2CuO_{7-\delta}$ film $\alpha = 13.97°$.

of the wedge angle α of the cone resonator for a wide range of angles α.

The sapphire resonator demonstrates a similar behavior as the resonator made of Teflon. However, some peculiarities of the sapphire resonator were revealed: 1) the quality factor of the resonator without the conducting endplate was practically unchanged with increase of angle and 2) the coefficient A_s considerably exceeded that of the Teflon resonator.

It was demonstrated experimentally that at $\alpha = 10 - 20°$, sapphire cone resonators can be used to study the surface impedance properties of HTS films. Compared with a cylindrical WGM resonator, it demands only one endplate, which simplifies the measurement process considerably.

In comparison to a sapphire hemisphere resonator, such a resonator is significantly easier to fabricate. Moreover, the resonators enable the control of the interaction of the microwave field and conducting endplate by varying the angle α of the cone.

In addition, the authors would like to emphasize that although the electrodynamic problem of the cone dielectric WGM resonators has not been presently solved analytically, their useful features have been found by using a careful comparison of experimental results with computer simulation. This opens perspectives for the application of this resonator technique in a wide frequency range, including the millimeter and optical wavelength range.

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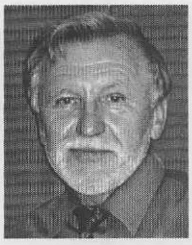

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