Single-Crystal Dielectric Resonators for Low-Temperature Electronics Applications

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***Abstract*—Computed properties of high-Q factor sapphire, YAG, $SrLaAlO_4$, $LaAlO_3$, rutile, and quartz dielectric resonators (DR's) operating on whispering-gallery TE_{011} and $TE_{01\delta}$ modes are presented in this paper. Resonators with a superconducting metal or partly superconducting partly metal shield are considered. For whispering-gallery-mode resonators, dielectric losses determine upper limit for their Q factors, while for TE_{011}-mode resonators, their Q factors are usually limited by conductor losses. Single-crystal $TE_{01\delta}$-mode resonators would have Q factors determined by both dielectric and conductor losses, and dominant loss mechanism depends on crystal losses and shield geometry. Geometric factors that allow evaluation of conductor losses of TE_{011}- and $TE_{01\delta}$-mode resonators are given for different DR structures.**

***Index Terms*—Cryogenic resonators, dielectric loss, dielectric resonators, permittivity, whispering-gallery modes.**

I. Introduction

DIELECTRIC resonators (DR's) have found extensive applications in modern electronic systems, e.g., as key elements of UHF, VHF, and microwave filters, stabilizing elements of microwave oscillators and parts of material property measurement fixtures [1]. Typical commercial DR's are made of ceramics having permittivities in the range of 24–90 and Qf products in the range of 5000–300 000 GHz (at room temperatures), where Q is the inverse of the dielectric loss tangent of dielectric material and f is the frequency of operation [2]. As temperature decreases to 4 K, dielectric losses in ceramic materials decrease, but typically only about 3–4 times with respect to their room-temperature values [3].

Single-crystal DR's exhibit much higher Q at cryogenic temperatures then their ceramic counterparts. Thus far, pure sapphire is known as the lowest loss dielectric material with a Q factor approximately equal to 10^{10} at 2 K and 10 GHz [4]. Outstanding properties of single-sapphire resonators enabled to employ them as the stabilizing element of microwave oscillators operating at cryogenic temperatures [5], and as resonators used in surface resistance measurements of superconductors [6], [7].

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Recently, several single-crystal dielectric materials have been investigated at cryogenic temperatures [8]–[15]. In this paper, we present predicted properties (Q factors, dimensions) of high-Q DR's that can be made of such materials. These resonators can operate at low temperatures with superconducting metal or partly superconducting partly metal shield.

II. Properties of Single-Crystal DR's

Most DR's are made as axially symmetric structures, typically as rods or cylinders. Any DR has an infinite number of resonant frequencies that depend on its dimensions, permittivity, and shielding conditions. Resonant frequencies can be determined quantitatively as eigenvalues of Maxwell's equations with appropriate boundary conditions. Different numerical methods like mode matching, Rayleigh–Ritz, and finite-element finite difference can be used to solve such a problem. For a given geometry of a DR, resonant frequencies are inversely proportional to the size of the resonant structure.

The Q factor of a DR, for any mode of operation, is determined by dielectric losses and by conductor losses in metal/superconducting enclosure, according to (1)–(3)

$$Q_0^{-1} = p_e \tan\delta + R_{\rm SS}/G_s + R_{\rm SM}/G_M \tag{1}$$

where

- Q_0 unloaded Q factor of the whole resonant structure;
- $R_{\rm SS}$ surface resistance of superconducting part of the shield;
- G_S geometric factor for superconducting part of the shield;
- P_e electric energy filling factor;
- $R_{\rm SM}$ surface resistance of metal part of the shield;
- G_M geometric factor for metal part of the shield.

Geometric factors G_S and G_M and electric energy filling factor p_e are defined as follows:

$$G_{S(M)} = \omega \frac{\iiint_{Vt} \mu_0 |\mathbf{H}|^2\, dv}{\int_{S_{S(M)}}\int |\mathbf{H}_\tau|\, ds} \tag{2}$$

$$p_e = \frac{\iiint_{Vd} \varepsilon |\mathbf{E}|^2\, dv}{\iiint_{Vt} \varepsilon(v) |\mathbf{E}|^2\, dv} \tag{3}$$

where

- Vd volume of DR;
- Vt volume of whole resonant structure;
- $\varepsilon(v)$ variable dependent permittivity inside the whole resonant structure;
- ε permittivity of DR material.

TABLE I
PROPERTIES OF SOME LOW-LOSS SINGLE-CRYSTAL MATERIALS AT 77 K

Material	f(GHz)	$\varepsilon_{r\perp}$	$1/\tan\delta_{\perp}$	$\varepsilon_{r\parallel}$	$1/\tan\delta_{\parallel}$
Sapphire	21.3	9.28	$8x10^{6}$	11.34	$2.5x10^{7}$
YAG	20.2	10.4	$2x10^{6}$	------	------
$SrLaAlO_4$	12	16.7	$5x10^{5}$	19.3	$2x10^{5}$
Quartz	17	4.44	$1.25x10^{5}$	4.63	$2x10^{5}$
Rutile	4.5	107	$2.1x10^{5}$	231	$1x10^{5}$
$LaAlO_3$ [8]	5.6	23.7	$2x10^{5}$	------	------

The above-mentioned formulas are valid for resonators made of an isotropic medium. Several single-crystals dielectrics are anisotropic and most of them exhibit uniaxial anisotropy. DR's made of uniaxially anisotropic crystals are usually made in such a manner that their symmetry axis is aligned with the anisotropy axis of the crystal. We will assume such a case in our discussion of single-crystal DR's. For a DR made of an oriented aniaxially anisotropic crystal, its Q factor can be determined by

$$Q_0^{-1} = p_{e\perp} \tan\delta_{\perp} + p_{e\parallel} \tan\delta_{\parallel} + R_{\rm SS}/G_S + R_{\rm SM}/G_M \tag{4}$$

where $p_{e\perp}$ and $p_{e\parallel}$ are electric energy filling factors perpendicular and parallel to DR's axis (anisotropy axis), respectively, and $\tan\delta_{\perp}$ and $\tan\delta_{\parallel}$ are appropriate dielectric loss tangents.

Dielectric properties of some materials that are the most suitable for manufacturing of low-temperature DR's are shown in Table I at 77 K [15]. At lower temperatures, Q factors may substantially differ between materials from different manufacturers since losses strongly depend on crystal purity.

At certain temperature ranges near 100 K (typically from 75 to 150 K), where the slope of dielectric loss tangent temperature curve approaches maximum for high-purity materials, dielectric losses can be approximated by power functions of absolute temperature as [15]

$$\begin{aligned} \tan\delta_{\perp} &= A_{\perp} T^{K_{\perp}} \\ \tan\delta_{\parallel} &= A_{\parallel} T^{K_{\parallel}}. \end{aligned} \tag{5}$$

Coefficients that allow evaluation of dielectric losses and Q factors of whispering-gallery mode resonators around 100 K at specific frequencies are given in Table II [15].

For high-purity sapphire, YAG, $LaAlO_3$, and rutile dielectric losses increase approximately linearly with frequency, thus for frequencies different then those specified in Table III, they should be appropriately scaled. For other materials dielectric loss dependence on frequency is not well known.

High-Q low-temperature DR's can operate on different modes and in different enclosures, as depicted in Figs. 1–3.

For cryogenic applications, the most popular are TE_{011}-mode resonators, shown in Fig. 1, due to their advantages such as

- surface current has only an azimuthal component, thus, electric contact between the lateral part of the metal cylinder and superconducting bottoms of the cavity is not important;
- geometric factor for TE_{011} mode is higher then for the neighboring HE_{111} and HE_{211} modes;
- mechanical construction of the whole resonator is simple;

TABLE II
DIELECTRIC LOSS FACTORS AND DIELECTRIC LOSS TEMPERATURE EXPONENTS AT 100 K

f(GHz)	Material	$A_{\perp}$(100 K)	$A_{\parallel}$(100 K)	$K_{\perp}$(100 K)	$K_{\parallel}$(100 K)
21.3	Sapphire	$5x10^{-16}$	$2x10^{-16}$	4.5	4.5
20.2	YAG	$1x10^{-12}$		3.0	
12	$SrLaAlO_4$	$1.6x10^{-9}$	$4x10^{-9}$	1.7	1.7
17	Quartz	$8x10^{-6}$	$5x10^{-6}$	≈0	≈0
4.5	Rutile	$3.2x10^{-11}$	$1.2x10^{-10}$	2.7	2.7

TABLE III
DIMENSIONS, GEOMETRIC FACTORS, AND UNLOADED Q FACTORS OF TE_{011}-MODE RESONATORS OPERATING AT 10 GHz AND 77 K ASSUMING SUFFICIENTLY LARGE DIAMETER OF A COPPER CYLINDER

Material	D (mm)	L (mm)	Gs (Ω)	Q_0 Rss=0.2 mΩ	Q_0 Rss=1 mΩ
Sapphire	9.79	9.79	517	$2.2 x10^{6}$	$5.0 x10^{5}$
Sapphire	13.64	6.82	226	$1.1 x10^{6}$	$2.2 x10^{5}$
Sapphire	17.84	5.95	161	$7.7 x10^{5}$	$1.6 x10^{5}$
YAG	9.27	9.27	500	$1.5 x10^{6}$	$4.5 x10^{5}$
YAG	12.90	6.45	214	$8.5 x10^{5}$	$2.0 x10^{5}$
YAG	16.86	5.62	152	$6.4 x10^{5}$	$1.5 x10^{5}$
$SrLaAlO_4$	7.38	7.38	410	$4.6 x10^{5}$	$2.4 x10^{5}$
$SrLaAlO_4$	10.21	5.10	171	$3.5 x10^{5}$	$1.3 x10^{5}$
$SrLaAlO_4$	13.32	4.44	121	$3.0 x10^{5}$	$1.0 x10^{5}$
$LaAlO_3$	6.22	6.22	349	$1.1 x10^{4}$	$8.5 x10^{4}$
$LaAlO_3$	8.58	4.29	145	$9.7 x10^{4}$	$6.3 x10^{4}$
$LaAlO_3$	11.19	3.73	101	$9.2 x10^{4}$	$5.3 x10^{4}$
Rutile	2.95	2.95	172	$8.2 x10^{4}$	$5.9 x10^{4}$
Rutile	4.05	2.03	69	$7.1 x10^{4}$	$3.9 x10^{4}$
Rutile	5.27	1.76	48	$6.6 x10^{4}$	$3.1 x10^{4}$

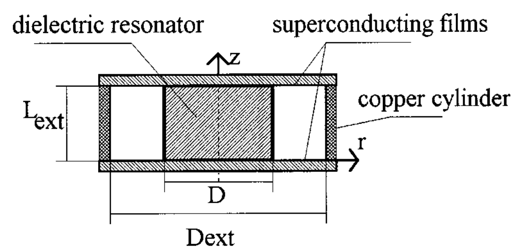

Fig. 1. High-Q TE_{011}-mode DR $L = L_{\rm ext}$.

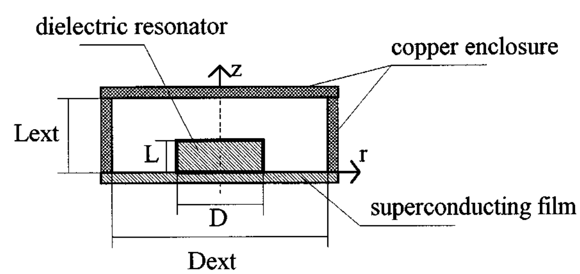

Fig. 2. High-Q $TE_{01\delta}$-mode DR.

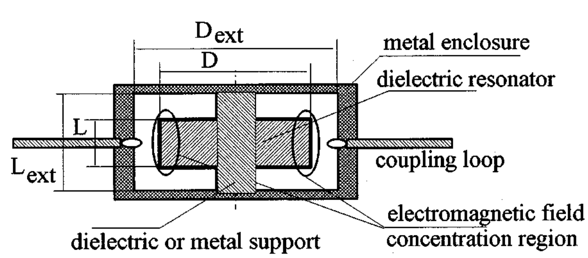

Fig. 3. Whispering-gallery-mode DR.

- size of the resonant structure is small, and frequency separation from the neighboring modes is large.

Computed properties of TE_{011}-mode DR's made of different materials and designed for resonant frequency 10 GHz and 77 K are shown in Table III. It was assumed in computations that DR's are terminated with two superconducting endplates having $R_{\mathrm{SS}} = 0.2\ \mathrm{m}\cdot\Omega$, $R_{\mathrm{SS}} = 1\ \mathrm{m}\cdot\Omega$, and that shielding copper cylinders had diameters at least three times larger then the diameters of dielectric rods. Under such an assumption, lateral copper losses can be neglected with respect to the losses in superconducting plates. As is seen in Table III, Q factors of resonators made of the lowest loss materials (sapphire, YAG) predominantly depend on geometric factors Gs and surface resistance of superconducting films. The higher aspect ratio (D/L) of the DR, the lower Q factor due to lower geometric factor. Data shown in Table III can be used to determine dimensions and Q factors depending on conductor losses for DR's operating at different frequencies. To evaluate dimensions for different frequencies, one has to multiply dimensions given in Table III by the ratio $10/f$, where f is the frequency of operation (in gigahertz). Geometric coefficients do not depend on frequency, thus, to obtain a Q factor depending on conductor losses, one has to divide the geometric factor by the surface resistance of the superconductor at the frequency and the temperature of interest. Q factor values of a TE_{011}-mode sapphire resonator with two superconducting endplates evaluated from (1) were confirmed experimentally by several researchers since this is the typical measurement setup for surface resistance measurements of superconductors [6], [15]. A sapphire TE_{011}-mode resonator operating at a frequency of 5.55 GHz with Yba_2Cu3O_7 superconducting plates at 80 K had a Q factor of about 3×10^6 [17].

Frequency–temperature dependence of dielectric losses is not well known for most materials, except sapphire, YAG, rutile, and $LaAlO_3$, especially at temperatures below 77 K; thus, the reader should refer to the literature [8]–[15] or manufacturer for the appropriate loss tangent data. At frequencies 10 GHz and above, Q factors of TE_{011}-mode resonators are predominantly determined by losses in superconductors so their Q factors decrease as $1/f^2$.

To decrease conductor losses, one can use DR's operating on the $\mathrm{TE}_{01\delta}$ mode. Geometric factors for resonators with one superconducting endplate, shown in Fig. 2, are roughly two times smaller then geometric factors for appropriate TE_{011}-mode counterparts with two superconducting endplates. The resonant frequencies of $\mathrm{TE}_{01\delta}$-mode resonators having dimensions as given in Table III are not equal to 10 GHz and depend on dimensions of metal enclosure, DR permittivity, and its aspect ratio. For a large size of enclosures, resonant frequencies of $\mathrm{TE}_{01\delta}$ modes are significantly smaller than for corresponding TE_{011}-mode resonators.

If the DR is moved away from all cavity walls, conductor losses for $\mathrm{TE}_{01\delta}$-mode resonators can be further decreased. They approach minimum when the resonator is placed at the center of the metal enclosure for certain optimum enclosure size. Optimum enclosure size depends on permittivity of the DR and its aspect ratio, as depicted in Fig. 4 for quartz, sapphire, and $LaAlO_3$ resonators having an aspect ratio equal to two. Geometric factor G in Fig. 4 is evaluated as the total geometric factor over all enclosure walls. For enclosure size, larger than optimum electric energy filling factors for $\mathrm{TE}_{01\delta}$ modes drop rapidly to very small values and electromagnetic-field distribution in the resonant structure converges to that for an empty cavity. In such a case, geometric factor approaches the same value as for empty cylindrical TE_{011}-mode cavity. For the reasons mentioned above, enclosure size of $\mathrm{TE}_{01\delta}$-mode resonators should not exceed optimum value. For the $\mathrm{TE}_{01\delta}$-mode $LaAlO_3$ resonator with an optimum shield made of copper operating at 10 GHz and 77 K, the Q factor value would be about 9.4×10^4. For the same resonator with a superconducting shield having $R_{\mathrm{ss}} = 0.2\ \mathrm{m}\cdot\Omega$, the Q factor would be 1.1×10^5. The Q factor for the sapphire resonator with an optimum size copper enclosure would be 2.1×10^5, but the same resonator with a full superconducting enclosure with $R_{\mathrm{ss}} = 0.2\ \mathrm{m}\cdot\Omega$ would have a Q factor 7.2×10^6 (1.7×10^7 for $R_{\mathrm{ss}} = 0$) One can conclude that for $\mathrm{TE}_{01\delta}$-mode resonators made of high-permittivity materials, whose losses are not extremely low, advantages of using superconducting enclosures are questionable, On other hand, for medium permittivity, extremely low-loss $\mathrm{TE}_{01\delta}$ DR's conductor losses are dominant.

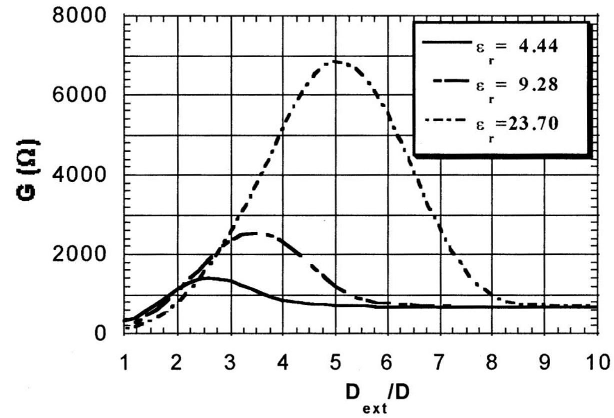

Fig. 4. Geometric factors versus dimensions of shielding metal cavity assuming $D_{\mathrm{ext}}/D = L_{\mathrm{ext}}/L$ and $D/L = 2$ for $\mathrm{TE}_{01\delta}$-mode DR's situated centrally at the cavity.

The highest Q factor DR's are those operating on higher azimuthal order modes. Such modes are called "whispering-gallery modes" since more then 90% of electromagnetic-field energy is concentrated near the lateral surface of a dielectric cylinder, as depicted in Fig. 3. For a properly chosen size of metal enclosure geometric factors for a high azimuthal number, modes approach extremely high values $(G > 10^7)$, thus, conductor losses can be neglected even if the enclosure is made of copper and dielectric loss is as low as in sapphire. For a high azimuthal number of whispering-gallery modes, one can assume that the Q factor is equal to the inverse of the dielectric loss tangent for a DR made of an isotropic crystal. For a DR made of an anisotropic crystal, Q factors should be evaluated using (4). Depending on electric energy filling factor values, whispering-gallery modes can be subdivided into quasi-TE $(p_{e\perp} \gg p_{e\|})$, quasi-TM $(p_{e\perp} \gg p_{e\|})$, or hybrid $(p_{e\perp} \approx p_{e\|})$. For quasi-TE and quasi-TM modes, one can use the inverse of $\tan\delta_\perp$ and the inverse of $\tan\delta_\|$, respectively, as a good ap-

TABLE IV
MEASURED PROPERTIES OF WHISPERING-GALLERY-MODE RESONATORS AT CRYOGENIC TEMPERATURES (ENCLOSURE SIZE $D_{ext} = 36$ mm, $L_{ext} = 21.9$ mm)

Material	Mode (azimuthal index)	T (K)	D	L	f (GHz)	Q
Sapphire	N1(9)	19	20.03	6.71	18.72	9.2×10^7
$SrLaAlO_4$	S1(5)	6.3	17.18	9.00	12.14	1.9×10^6
YAG	S1(10)	6.2	21.65	7.87	20.19	1.3×10^7

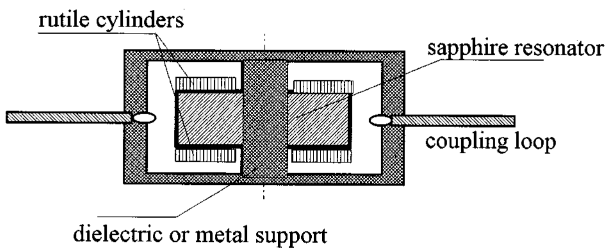

Fig. 5. Composite sapphire–rutile whispering-gallery-mode resonator.

proximation for their Q factors. In practice, whispering-gallery modes are not easy to use due to increasing resonant frequency spectrum density at higher frequencies and difficulties with mode identification. Preliminary filters should be used to eliminate parasitic modes. One should notice, however, that whispering-gallery modes offer the highest known Q factor values with no power dependence (contrary to TE_{011}-mode resonators with superconducting endplates). Table IV presents parameters of a few whispering-gallery-mode resonators that were used in earlier experiments [15] performed by one of the authors of this paper.

Frequency–temperature turning points for high-purity single-crystal materials are typically at the temperature range of 5–40 K. Turning-point temperature and curvature of the frequency–temperature function depend on the kind and amount of paramagnetic impurities that are always present even in high-purity crystals. Frequency stabilization in whispering-gallery-mode resonators made of high-purity crystals is associated with opposite slopes of frequency–temperature variations due to the thermal expansion of material and paramagnetic susceptibility. For anisotropic crystals, susceptibility is anisotropic and frequency–temperature dependences for quasi-TE and quasi-TM modes are different.

Using composite sapphire–rutile resonators, shown in Fig. 5, or specially doped crystals (e.g., titanium-doped sapphire), it is possible to increase turning-point temperature to 50–150 K [18], but with reduced Q factor values with respect to pure sapphire resonators.

III. CONCLUSIONS

The whispering-gallery-mode single-crystal resonators provide the highest possible Q factors of three types of DR's. However, typically dimensions of whispering-gallery-mode resonators are about 3–4 times larger than the TE_{011}-mode resonators at a given frequency. Hence, for frequencies below 10 GHz, the TE_{011}-mode resonators with superconducting shields are recommended in most applications (except for ultra-stable oscillators and extremely high-power applications). For microwave frequencies above 40 GHz, the whispering-gallery resonators are ultimate choice due to their moderate dimensions at high frequencies and much higher Q factors than other types. At frequencies between 10–40 GHz, the $TE_{01\delta}$ resonators with a metal or composite shield (partly superconducting partly metal) of properly chosen size would provide, in most cases, the best performance.

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