Properties and Applications of HTS-Shielded Dielectric Resonators: A State-of-the-Art Report

Norbert Klein, Andreas Scholen, Norbert Tellmann, Claudio Zuccaro, and Knut Wolf Urban

Abstract— **High temperature superconductor (HTS) shielded dielectric resonators (DR's) have demonstrated to provide quality factors Q between 5×10^5 and several 10^6 at frequencies up to 20 GHz and levels of dissipated rf power in the range of Watts. As dielectric materials, high purity single crystals of sapphire, $LaAlO_3$, and rutile exhibit sufficiently low microwave losses. There are two main areas of application which are considered to benefit from HTS-shielded DR's, namely low-phase-noise oscillators for radar systems and digital communication, and high-power filters for satellite communication. Projections for phase noise are −145 dBc/Hz at 1 kHz offset from the carrier frequency, a value of −110 dBc/Hz at 1 kHz was measured recently for an oscillator with a carrier frequency of 5.6 GHz. Modeling of filters based on resonators with Qs in the 10^6 range indicates their ability to reduce the rf power dissipation apparent in the output multiplexers of communication satellite payloads. Presently, schemes for resonator coupling and tuning while maintaining high Qs are under development.**

I. Introduction

THE UTILIZATION of the low microwave surface resistance R_s of epitaxially grown high temperature superconductor (HTS) films is restricted to planar surfaces. Besides planar circuits based on (micro)striplines, coplanar lines, or lumped elements, HTS shielded dielectric resonators (DR's) benefit from the low R_s values of HTS films. Basically, a HTS shielded DR consists of a disk shaped DR with two HTS endplates attached or arranged close to the endplates of the disk (Fig. 1). For the majority of applications TE_{0np} modes are considered. For these modes only a negligible amount of losses arises from the cylinder wall, which is usually machined from high purity copper. The modeling of the electromagnetic (em) fields of the resonator in Fig. 1 can be performed using semianalytical approaches based on a representation of the em fields in terms of one [1], [2] or a finite number [3] of TE_{0n} mode(s) of a shielded dielectric rod waveguide. For the rigorous analysis of HTS-shielded DR's taking into account coupling apertures or a possible anisotropy of the permittivity of the dielectric disk numerical methods like e.g. the computer code "MAFIA" [4], [5] were used successfully.

II. Losses in Single-Crystalline Dielectric Materials

Among the single-crystal materials with high permittivity sapphire ($\epsilon_r = 9.4$), MgO ($\epsilon_r = 9.7$), $LaAlO_3$ ($\epsilon_r = 23.4$),

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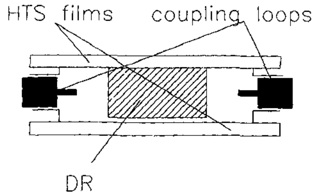

Fig. 1. Schematic drawing of an HTS-shielded DR.

and rutile ($\epsilon_r = 105$) exhibit considerably low values of the loss tangent $\tan\delta$ [6], [7]. Sapphire was investigated from 9 to 150 GHz indicating a linear frequency dependence and a T^{4-5} temperature dependence of $\tan\delta$ from 70 to 150 K with $\tan\delta(77\ \mathrm{K}, 10\ \mathrm{GHz}) \approx 2 \times 10^{-7}$ [8], [9]. The observed temperature dependence of $\tan\delta$ was found to be in good agreement with the theoretical model of Sparks, King and Mills [10], which describes intrinsic losses caused by the interaction of em waves with the phonon system. In addition to the strongly temperature dependent intrinsic losses, the level of the nearly temperature independent residual losses caused by defects is of the order of 10^{-9}–10^{-6} depending on the quality of the crystals. The losses of MgO were found to be in the 10^{-6} range [6]. However, there is no advantage of MgO-DR's as sapphire has about the same ϵ_r, lower losses and provides an ultimate mechanical and chemical stability. From the materials with higher ϵ_r, $LaAlO_3$ was found to exhibit quite low losses. Fig. 2 shows the unloaded quality factor Q_0 versus temperature for an HTS-shielded DR with different $LaAlO_3$ cylinders of 15.2 mm diameter and 7.6 mm height (TE_{011}-mode). Except in the temperature range close to T_c, Q_0 is dominated by the losses in the dielectric cylinder, i.e. Q_0^{-1} is approximately equal to $\tan\delta$. According to Fig. 2 the highest Q_0 values of 2×10^6 at 4 K were measured with a Czochralski grown cylinder with its twin boundaries uniformly oriented parallel to the cylinder endplate throughout the entire cylinder (= single domain, circles), However, above about 35 K Q_0 decreases strongly leading to a crossover with the $Q_0(T)$ data measured with the Verneuil grown cylinder (squares) at 50 K. The Verneuil grown cylinder has a typical domain size of a few millimeters. The data marked by crosses and triangles were measured using cylinders with less than five large domains grown by Czochralski (crosses) and Verneuil (triangles), respectively. It is obvious from Fig. 2 that the loss tangent of $LaAlO_3$ is strongly affected by the twinning domains and by impurities. For the Czochralski grown material the level of impurities is considered to be smaller in comparison to the Verneuil material. This may be the reason for the high Q_0 values at low temperatures.

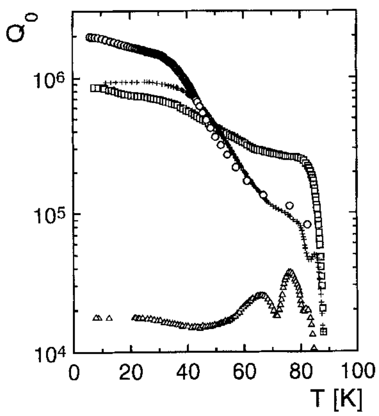

Fig. 2. Unloaded quality factor versus temperature for a HTS-shielded DR at 5.6 GHz measured with single domain Czochralski (circles), small domain size Verneuil (squares), large domain size Czochralski (crosses) and Verneuil (triangles) grown $LaAlO_3$ cylinders (from [25]).

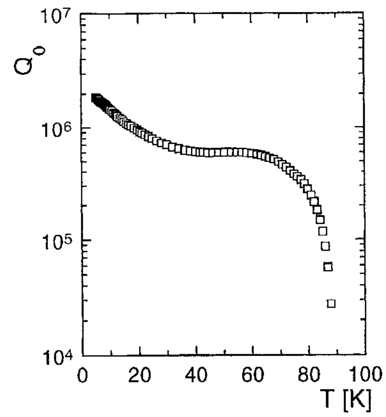

Fig. 4. Unloaded quality factor versus temperature for an HTS-shielded sapphire DR at 11 GHz.

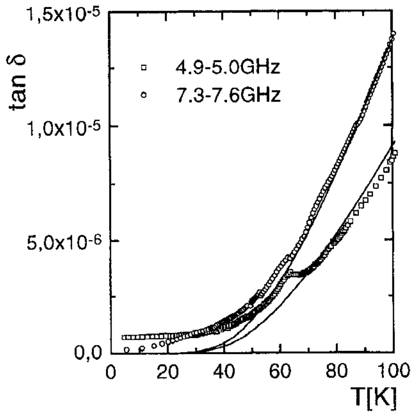

Fig. 3. Loss tangent $\tan\delta$ of rutile measured with the 4 mm diameter ($f = 7.3$–7.8 GHz) and with the 6 mm diameter rutile cylinder ($f = 4.9$–5.2 GHz). The full lines represent theoretical calculations based on a model described in [10].

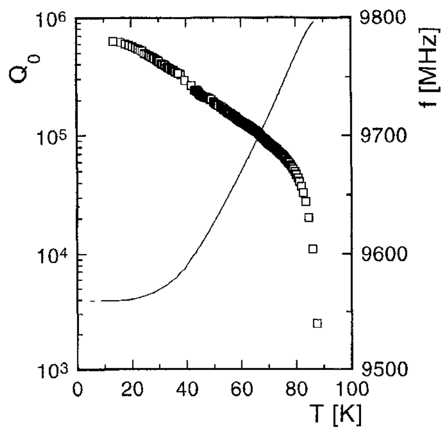

Fig. 5. Q_0 (triangles) and resonance frequency (full line) versus temperature measured with an HTS-shielded rutile DR (from [7]).

For applications in the low GHz range rutile is of particular relevance due to its high permittivity of 85 at room temperature and 110 at 4 K (for electric fields parallel to the crystallographic a, b plane) [7]. Fig. 3 shows $\tan\delta(T)_{a,b}$ at two different frequencies, measured by a dielectric resonator technique. Above the kink apparent in one data set $\tan\delta$ exhibits a frequency and temperature dependence according to $fT^{2.5}$, which is in good agreement with the theoretical model by Sparks, King and Mills (full lines in Fig. 3, calculated according to [10] using phonon frequencies from the Δ_3 phonon branches, see phonon dispersion relations of rutile in [11]).

III. Properties of HTS-Shielded Dielectric Resonators

The highest quality factors were obtained with HTS-shielded sapphire DR's at C-band frequencies [12]. Fig. 4 shows the unloaded quality factor versus temperature for an HTS shielded sapphire DR using to $YBa_2Cu_3O_7$ films of one inch in diameter at 11 GHz. Fig. 5 shows Q_0 (triangles) and resonance frequency (full line) versus temperature for a HTS shielded rutile DR at about the same frequency. Due to the high permittivity of rutile this resonator is extremely small in size, the diameter and height of the resonant volume is 8 mm and 2 mm, respectively [7]. From the linear frequency dependence of the loss tangent and the f^2 dependence of the surface resistance of HTS films Qs of about 10^6 at 77 K are expected at 1.8 GHz, which is an important frequency for mobile communication. At 1.8 GHz a YBCO shielded rutile DR would require two YBCO films of only two inches in diameter. One drawback of rutile is the strong temperature dependence of the permittivity resulting in a temperature coefficient of the resonance frequency of 500 ppm/K for the HTS-shielded rutile DR at 60 K (Fig. 5).

However, the large negative temperature coefficient of ϵ_r (i.e. the positive temperature coefficient of the resonance frequency of a rutile DR) can be utilized to provide a passive compensation of the negative temperature coefficient of the resonance frequency due to thermal expansion and the temperature dependence of the penetration depth in superconductors. As an example, Fig. 6(a) shows a resonator geometry with a thin rutile disk of thickness d arranged inside the shielding cavity of a sapphire DR. The dashed line in Fig. 6(b) represents the measured temperature coefficient of the resonance frequency of the resonator in Fig. 6(a) without the rutile disk at T = 70K, which is due to thermal expansion and temperature change of the penetration depth of the HTS-films covering the top and bottom plate of the shielding cavity. The squares

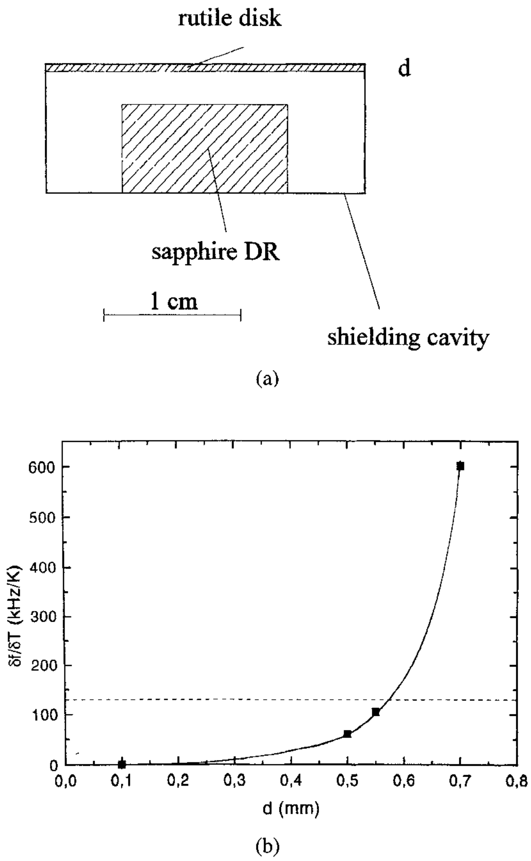

Fig. 6. (a) Passive compensation of the temperature coefficient of a shielded sapphire DR by a thin rutile disk of thickness d. In (b), the dashed line represents the temperature coefficient of the resonance frequency of the resonator shown in (a) without the rutile disk at T = 70K. The squares represent calculated values of the change of the resonance frequency with temperature due to the temperature dependence of ϵ_r of rutile.

represent calculated values of the change of the resonance frequency with temperature due to the temperature dependence of ϵ_r from [7]. According to this calculation performed with the computer code "MAFIA" [4], [5] compensation of the temperature coefficient occurs at a thickness of the rutile disk of 0.56 mm. The fraction of electric field energy stored in the rutile disk is a few percent of the total energy stored in the resonator, i.e. the loss contribution of the rutile disk becomes negligible.

The maximum power level at which high Qs are maintained is determined by the lower critical field H_{c1} of the film, which is related to the critical current density j_c by $j_c = H_{c1}/\lambda$, with λ being the penetration depth of the magnetic field. Typically, at 4 K (77 K) the critical current density is $5 \times 10^7 (5 \times 10^6)$ A/cm^2, leading to critical magnetic induction values of $B_{c1}(4\text{ K}) = 100$ mT ($\lambda = 150$ nm) and $B_{c1}(77\text{ K}) = 16$ mT ($\lambda = 260$ nm). The circulating power, i.e. the product of power dissipated in the resonator P_0 and Q_0, is proportional to the square of magnetic field. The maximum circulating power can be calculated from the maximum rf magnetic field on the surface of one of HTS films:

$$B_{c1}^2 = \alpha_B^2 (P_0 Q_0)_{\max}. \quad (1)$$

The field calibration factor α_B was calculated using the "MAFIA" code. α_B depends on the resonator geometry and on the mode. As an example, for a DR at 10 GHz (TE_{011}-mode) with diameter = 2× height the $(P_0 Q_0)_{\max}$ values at 4 K (77 K) are 2.8×10^8 W (7×10^6 W) for sapphire ($\alpha_B = 6.06 \times 10^{-6}$ T/W$^{1/2}$). Therefore HTS shielded DR's have the capability to handle levels of dissipated power in the range of Watts (depending on Q_0). According to the data given in [12] and more recent data given in [14] the nonlinear effects at lower power levels can be very small (depending on the quality of the HTS film [14]), in contrast to most of the HTS planar devices [13] (except those using modes without rf currents parallel to edges, see [14]).

IV. Oscillators

There is a strong demand for low-phase-noise oscillators from several areas of applications. First, Doppler radar systems would gain sensitivity upon improving the oscillator phase noise. Secondly, the bit error rate in high speed digital communication systems could be decreased, especially in high order Quadrature Amplitude Modulation (QAM) systems where phase jitter or noise close to the carrier causes increased uncertainty in the phase angle of the carrier prior to and during IF processing [15]. Finally, there is a demand for low phase noise standards, in particular at frequencies above 20 GHz. All these applications are considered to be in the frequency range from 5 to 40 GHz. At lower frequencies it is believed that HTS oscillators can hardly compete against SAW oscillators.

Fig. 7 shows the measured phase noise of a 5.6GHz oscillator consisting of a HTS shielded $LaAlO_3$ DR used as a feedback of a room temperature FET amplifier. At an offset frequency of 1 kHz a phase noise as low as −110 dBc/Hz was measured, values of −100 dBc/Hz were reported recently [16] for an HTS shielded sapphire DR at about the same frequency. Above an offset frequency of about 10 kHz the phase noise is below the noise floor of the phase noise measurement system (dashed line). The full line represents a calculation according to the Leeson formula [17]:

$$L(f) = 10 \times \log\left[\left(1 + \frac{f_0^2}{4Q_l^2 f^2}\right)\left(\frac{\alpha}{f} + \frac{GFkT}{P}\right)\right]. \quad (2)$$

Using $f_0 = 5.6$ GHz, $P = +15$ dBm (amplifier output power), $G = 20$ dB (ampifier gain), $F = 1$ dB (amplifier noise figure), $T = 293$ K (amplifier operation temperature), $Q_l = 150\,000$ (loaded quality factor) the data below 2 kHz can be fitted well using a cutoff frequency $f_c(\alpha/f_c$ is equal to the white noise, i.e. $f_c = \alpha P/(GFkT)))$ of 3 MHz. This is a typical value for FET amplifiers [18]. Using bipolar transistors instead of FET's with typical cutoff frequencies of about 10 kHz [19] a reduction of phase noise by 20 dB, i.e. to −130 dBc/Hz at 1 kHz is expected. According to (2) a further reduction should also be achievable by higher quality factors. However, at present a limitation of the oscillator performance by possible $1/f$ noise of the HTS resonator cannot be excluded and therefore further investigations are necessary. A reduction of phase noise to values much below the Leeson expectation can also be achieved by using more advanced oscillator circuits [15], [20]. Recently, phase noise values between −130 dBc/Hz and −145 dBc/Hz at 1 kHz were demonstrated

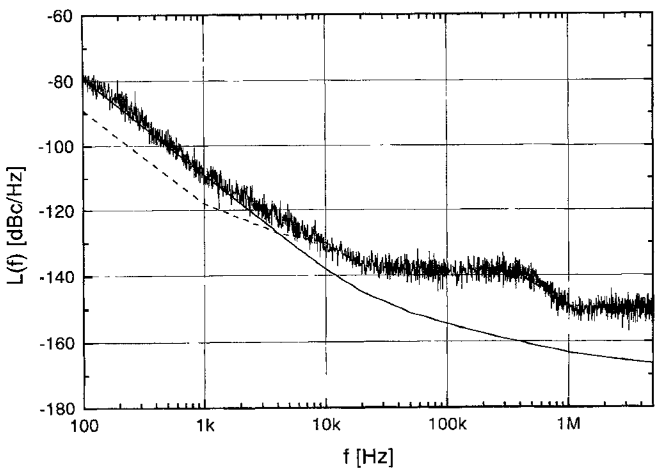

Fig. 7. Measured phase noise of a 5.6 GHz HTS oscillator. The dashed line represents the noise floor of the phase noise measurement system. The full line was calculated according to (2) using $f_0 = 5.6$ GHz, $P = +15$ dBm, $G = 20$ dB, $F = 1$ dB, $T = 293$ K, $Q_l = 150000$, and $f_c = 3$ MHz.

using either a whispering-gallery-mode sapphire resonator at $T = 0°C$ [15, 21] or cryogenic temperatures [22] as well as HTS shielded sapphire DR's in low order TE_{01} modes [23], all of these using PLL based feedback circuits. The disadvantage of such oscillators is the enhanced complexity of the circuit, which makes the realization of all-cryogenic hybrid oscillators more difficult. Problems which are currently addressed are the implementation of compact cryocoolers with emphasis on temperature stability and low microphonics.

V. Filters

Presently, the most promising area of applications for filters based on HTS shielded DR's are output multiplexers in communication satellites. Typically, power levels of 10–100 W are passed through filters of less than 1% bandwidth at 4–20 GHz. The insertion loss values of conventional waveguide filters is in the order of a few tenths of a dB giving raise to Watts of power loss in the output multiplexer. The reduction of insertion loss by the use of filters based on resonators with higher Qs is considered to decrease the required output power of the travelling wave tube amplifiers. Weight reduction, however, is more a concern of the input multiplexers where HTS planar filters are considered to replace the waveguide and conventional DR filters.

As an example, the calculated insertion loss of an 8 pole Tchebyschev filter with 1% bandwidth is about 0.25 dB for conventional resonators with Q_0s of 20 000 and 0.007 dB for HTS-shielded DR's with Q_0s of 10^6 [24]. Assuming a total power of 100 W to be passed through the superconducting filter, the $P_0 Q_0$ of each resonator is about 20 000 W, which corresponds to rf field amplitudes well below the critical values (see Eq. 1). The total power dissipation in the filter would be 160 mW in comparison to 5.6 W for the normal conducting version. However, possible losses in the input/output connectors have to be minimized as well, i.e. coaxial coupling as shown in Fig. 1 will not be allowed.

To the best of our knowledge, filters consisting of resonators of such high Q values have not been built yet. One problem is connected with frequency tuning. Here schemes adapted from conventional DR's (e.g. tuning screws in the shielding cavity) are considered to result in an untolerable Q degradation. COM-DEV recently demonstrated a dual mode DR filter with an HTS film acting as mirror plane inside the shielding cavity [26]. However, only Qs of 10^4 were achieved. In comparison to waveguide filters with about the same resonator Q, the benefit is a reduction of mass and size of input multiplexers. One possible way of tuning without Q degradation would be a variable gap between one of the HTS films and the dielectric cylinder (Fig. 1). However, the mechanical layout of such a tuning structure needs to be very insensitive against vibration.

VI. Conclusion

HTS shielded DR's have the potential to provide quality factors in the 10^5–10^6 range at levels of Watts of dissipated rf power. Such performance cannot be achieved by non cryogenic resonators. Therefore HTS-shielded DR's have a large potential to fulfill performance requirements of future microwave radar and communication systems. In contrast to the HTS films where significant improvements of the microwave properties are not likely to be expected, the exploration and optimization of dielectrics at cryogenic temperatures offers a new device performance related field of material research. In order to make practical use of HTS-shielded DR's in microwave radar and communication systems the engineering tasks associated with resonator coupling, tuning and cooling by cryocoolers need to be well defined in the nearest future by considering system specifications.

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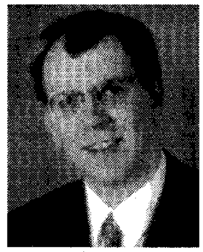

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