Microwave probing of bulk dielectrics using superconducting coplanar resonators in distant-flip-chip geometry

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Lock-in Amplifiers up to 600 MHz





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ABSTRACT

Dielectric measurements on insulating materials at cryogenic temperatures can be challenging, depending on the frequency and temperature ranges of interest. We present a technique to study the dielectric properties of bulk dielectrics at GHz frequencies. A superconducting coplanar Nb resonator is deposited directly on the material of interest, and this resonator is then probed in distant-flip-chip geometry with a microwave feedline on a separate chip. Evaluating several harmonics of the resonator gives access to various probing frequencies in the present studies up to 20 GHz. We demonstrate the technique on three different materials (MgO, LaAlO₃, and TiO₂), at temperatures between 1.4 K and 7 K.

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I. INTRODUCTION

The dielectric properties of various insulating materials are highly interesting and topic of ongoing research.^{1–6} However, there is no single generic method to probe dielectrics at certain frequencies or low temperatures, and different high frequency techniques can access the desired properties in the GHz range.⁷ Especially, resonant techniques are suited since they provide good accuracy.^{8–10} The goal of this study is to characterize bulk dielectrics with a new resonant approach by probing multiple discrete GHz frequencies at cryogenic temperatures.

Planar superconducting microwave resonators play an important role in solid state research, including cryogenic spectroscopic studies.^{11–24} One can simultaneously probe various harmonics of a fundamental resonance frequency and perform measurements at low temperatures, even in setups with limited space for the sample probe, such as in high magnetic fields or at mK temperatures.^{19,25–31} Superconducting resonators can reach very high quality factors³² and thus high sensitivity for the dielectric under study.^{33–35,39} A further advantage is the well-established lithographic fabrication that allows for straightforward modification of the resonator design to adjust to specific frequency or geometry demands. The approach presented here also eliminates a common problem of related

experiments, namely air gaps, which strongly reduce accuracy or even inhibit completely the desired measurements,⁷ e.g., if one places an unpatterned dielectric on top of a coplanar resonator fabricated on a separate chip.^{39,40} In our approach, the superconducting coplanar waveguide (CPW) resonator is directly deposited on top of the bulk sample under study and then excited with an external microwave feedline. We chose the superconductor Nb as resonator material since its fabrication is well established,^{41–43} such resonators have already been studied in great detail,^{44,45} and their properties can be optimized depending on the performance parameters of Cryogenic microwave resonators in flip-chip geomeinterest.46 try have recently gained attention as quantum devices that employ well-characterized materials,⁴⁹⁻⁵² while our goal is to study materials with unknown dielectric properties, with possibly very large dielectric constants.^{3,5}

II. RESONATOR DESIGN: DISTANT-FLIP-CHIP GEOMETRY

In Fig. 1, the distant-flip-chip geometry is displayed. The superconducting Nb coplanar $\lambda/4$ -resonator is fabricated with thickness t, center conductor width W, and gap width S on the studied sample. The sample is then flipped and placed over a coplanar feedline, made



FIG. 1. (a) Schematic of distant-flip-chip geometry. The sample (transparent green) with the deposited CPW λ /4-resonator is flipped over a coplanar transmission line on a substrate (blue) but kept at a distance *h*. (b) Schematic cross section of CPW, indicating distance *h* between the chip and the substrate, inner conductor width *W*, gap S between inner and outer conductors, and thickness *t* of the resonator. *I_c* is the coupling length. (c) Photograph of the distant-flip-chip arrangement.

of Cu on a sapphire substrate, in a certain distance h such that both conductive layers are facing each other. The outer conductor of the feedline is designed such that most of the feedline chip surface facing the resonator chip is not covered by the Cu. The resonator has a coupling arm with length l_c and with a closed end, which is centrally placed above the center conductor of the feedline, while the opposite resonator end is open. As displayed in Fig. 1, the resonator is shaped with a meander structure, which increases its total length and therefore reaches a smaller fundamental resonance frequency. Via inductive coupling,⁵² the microwave signal is transmitted from the feedline and the $\lambda/4$ -resonator is excited. The distant-flip-chip design has the advantage that the microwave signal couples through the open space between sample and feedline chips, thus preventing losses and depolarization effects. The distance h and the coupling length l_c are of crucial importance regarding the microwave coupling and thus functionality and performance of the distant-flip-chip geometry.

There are some challenges with this approach, especially concerning control of the coupling into the resonator, certain sample requirements, and the mounting of the resonator chip. The signal may not couple sufficiently into the resonator to excite the fundamental and higher harmonic modes since the permittivity of the sample is unknown, and therefore, the impedance of the resonator cannot be adjusted correctly. Furthermore, the mounting of the chip influences the coupling into the resonator. The distance must be set appropriately to optimize the coupling into the resonator. Additionally, the sample needs to be flat with a polished surface and a size of at least a few mm to apply the distant-flip-chip geometry.

III. SIMULATIONS AND THEORY

The distant-flip-chip geometry is checked with simulations for its suitability using *CST Microwave Studio*, and the results can be compared to theoretical predictions obtained with the conformal mapping theory.^{54,55} From the latter, closed-form expressions for the effective dielectric constant ϵ_{eff} are obtained. Within this technique, the CPW is split into partial regions and the electric field is assumed to fill each of them homogeneously. Then, the capacitance of each part is found, and the sum gives the total capacitance. The effective dielectric constant ϵ_{eff} is then calculated by the ratio of the total capacitance of the CPW and the capacitance in the absence of all dielectrics. Assumptions for this technique are that the conductors have perfect conductivity, the structure is lossless, the dielectrics are isotropic, and the electric field fills each partial region perfectly.

In Fig. 2, the resonance frequency as a function of the sample permittivity is displayed, obtained either by simulations or analytical calculation. For the latter, the resonance frequencies v_n decrease with the increase in permittivity following

$$v_n = \frac{nc}{4l\sqrt{\epsilon_{\rm eff}}},\tag{1}$$

with *n* being the number of mode, *c* being the vacuum speed of light, *l* being the length of the resonator, and ϵ_{eff} being the effective dielectric constant of the resonant design. Since the distant-flip-chip geometry utilizes a $\lambda/4$ -resonator, only odd multiples (n = 3, 5, ...) of the fundamental frequency (n = 1) can be excited. The simulated results, marked in Fig. 2 as symbols, match the analytical predictions marked as full lines. The permittivity of the sample dominates ϵ_{eff} , which results in a shift to smaller resonance frequencies for an increasing permittivity.



FIG. 2. Fundamental and harmonic resonance frequencies of a distant-flip-chip geometry for sample permittivities up to 300. The distance of the chip is $h = 50 \ \mu m$ and the coupling length of the resonator is $l_c = 500 \ \mu m$. Symbols indicate simulation results, whereas full lines are obtained analytically from conformal mapping theory.

IV. MEASUREMENTS AND RESULTS

Three different dielectric materials are used to test the approach: MgO, LaAlO₃, and TiO₂. The dielectric response of each of them at cryogenic temperatures and GHz frequencies is basically constant as a function of temperature and frequency,⁵⁶ and with ϵ values roughly around 10, 25, and 200, they cover the range that is typically encountered for crystalline solids at low temperatures. Coplanar Nb resonators are deposited onto the three substrate materials, and they are then mounted in distant-flip-chip geometry above the feedline chip. The height *h*, typically around 40–50 μ m, is adjusted manually with the help of some vacuum grease at the corners of the resonator chip and then fixed with Fixogum. Three different resonator lengths are chosen for the LaAlO3 and TiO2 substrates, respectively, and one length for the MgO substrates. All resonators have a center conductor width of $W = 120 \,\mu\text{m}$, a gap width of $S = 50 \ \mu m$, and Nb thickness $t = 300 \ nm$. Microwave transmission spectra (complex transmission coefficient \hat{S}_{21}) are then obtained using a vector network analyzer (VNA) for frequencies up to 20 GHz, while the resonator is cooled in a ⁴He cryostat with variabletemperature insert (VTI), down to a base temperature around $T \approx 1.4 \text{ K.}^{6}$

In Fig. 3, an exemplary spectrum of a resonator on TiO₂ is displayed. The resonance dips can be clearly identified. Since these resonances are much sharper than the other features that contribute the frequency-dependent background of the overall spectrum, we can perform robust measurements even without the additional efforts of a cryogenic microwave calibration.^{62–64} The number of possible discrete discernible resonances depends strongly on the length *l* of the resonator and the permittivity of the studied sample according to Eq. (1). For further analysis, the resonances in \hat{S}_{21} are fitted with a complex function that consists of a Lorentzian for the resonance, a phase term to accommodate the influence of the overall transmission line, and a linear term plus offset to correct for the



FIG. 3. Microwave transmission spectrum for a superconducting resonator on TiO₂, with length *I* = 11 533 μ m, mounted in flip-chip geometry above a feedline and measured at 1.4 K. For comparison, the transmission spectrum of a bare feedline, measured at room temperature, is shown.⁶¹ The insets (a) and (b) show two respective resonance dips with higher resolution and the corresponding Lorentzian fits.

frequency-dependent background near the resonance,⁶⁵ which directly yields the resonance frequency v_n , as depicted in the insets (a) and (b) in Fig. 3.

These identified resonance dips are then tracked in temperaturedependent measurements up to a temperature of 9 K. In Fig. 4(a), the resonance frequencies of the fundamental mode and a high harmonic of this resonator are shown. In the lower part of this panel, the uncorrected frequencies can be seen. Upon increasing temperature, they first remain constant before shifting to lower frequencies. Since the permittivity of TiO₂ is temperature-independent within this range, this temperature dependence of the resonator has to be caused by the temperature-dependent superconducting properties of the Nb thin film. This can be modeled based on the London equations, which give an expression for the so-called London penetration depth.⁶⁶ The penetration depth λ is temperature dependent and diverges when approaching the critical temperature T_c . For temperatures close to T_c of the Nb, it can be described with an empirical equation⁶⁷

$$\lambda(T) = \frac{\lambda_0}{\sqrt{1 - \left(\frac{T}{T_c}\right)^4}},\tag{2}$$

with λ_0 the penetration depth at zero temperature. The temperaturedependent $\lambda(T)$ affects the impedance of the coplanar resonator,⁶⁸



FIG. 4. Temperature dependence of resonator properties and determination of dielectric constant for a Nb resonator on the TiO₂ substrate. (a) Resonance frequencies of the fundamental (n = 1) and n = 17 mode for temperatures up to T = 7.2 K. The lower data are the uncorrected resonance frequencies, where the temperature-dependent penetration depth of Nb causes a shift. The upper data are the corrected resonance frequencies with the effects of the superconductor subtracted. For temperatures close to T_c , the displayed analytical equation is applicable and can describe the frequency shift due to the change in the impedance. (b) Permittivity (real part ϵ_1 of dielectric constant) of the TiO₂ substrate as determined by this procedure. (c) Temperature-dependent quality factor Q of the resonances for several of the harmonics.

and the impedance in turn is related to the resonance frequency of the resonator via the effective dielectric constant, and thus, a frequency shift occurs. With the increase in temperature and increase in penetration depth, the resonances shift to lower frequencies. Above T_c , the Nb turns to its non-superconducting metallic state with high resistivity,⁶⁹ and the resonance dips in the measured transmission spectra disappear. The temperature-dependent frequency shift applies for the fundamental and harmonic modes with index *n* and can be described with

$$v_n = \frac{v_{0,n}}{\sqrt{1 + \frac{\Gamma}{2Z_0} \frac{\lambda_0}{\sqrt{1 - \left(\frac{T}{T_c}\right)^4}}}},$$
(3)

with the shifted resonance frequency v, the resonance frequency v_0 of the unperturbed CPW for temperature T = 0, a geometrical factor Γ , the characteristic impedance Z_0 of the superconducting resonator, and the penetration depth λ_0 at T = 0. Both Γ and Z_0 are fixed parameters and calculated with the conformal mapping theory.

The fit to the measured data in Fig. 4(a) shows that this approach properly describes the temperature dependence. Therefore, we can now "correct" the measured data by converting them to the case of the ideal conductor or, in other words, a superconductor with vanishing penetration depth. These "corrected" resonance frequencies are shown in the upper part of Fig. 4(a). For both modes, they are basically constant for the measured temperature range. Thus, they are now cleared of the temperature-dependent influence of the Nb, and they represent the intrinsic dielectric properties of the substrate material under study. This procedure might be paraphrased by taking into account the temperature-dependent kinetic inductance of the superconductor.^{70,71}

The fits following Eq. (3) reveal values for the parameters T_c and λ_0 , and thus, they give information about the superconducting properties of Nb. In Table I, these parameters for the Nb films on the three used dielectrics are listed. They are averaged for each material since the bulk was sputtered first and afterward cut and structured. It is well known that the quality of Nb thin films is very sensitive to the growth conditions, and therefore, the superconducting properties of Nb films can vary substantially. This is indeed what we find for the three different substrates, e.g., $T_{c,Nb}$ ranging between 6.91 K and 8.15 K, all of them well below the value of 9.2 K for bulk Nb. Here, we point out that the Nb deposition was not optimized for the different substrates, but the same growth recipe was applied to all of them. This was intentional, as our goal is not to study or optimize the Nb growth on a particular dielectric of interest but obtain results that are independent of the quality of a particular superconducting film.

TABLE I. Critical temperature $T_{c,\text{Nb}}$ and penetration depth λ_0 at T = 0 for the Nb resonators on the respective dielectrics obtained with fits according to Eq. (3). The values are averaged for all according fits, and $\Delta T_{c,\text{Nb}}$ and $\Delta \lambda_0$ display the respective statistical errors.

Dielectric	$T_{c,\mathrm{Nb}}$ (K)	$\Delta T_{c,\mathrm{Nb}}$ (K)	λ_0 (nm)	$\Delta\lambda_0 (nm)$
LaAlO ₃	6.91	0.38	784.26	169.62
TiO ₂	7.50	0.12	718.63	137.71
MgO	8.15	0.03	439.09	53.84

The three cases in Table I show that the quality of the Nb films is lowest for LaAlO₃, with lowest $T_{c,Nb}$ and broadest range $\Delta T_{c,Nb}$ of the superconducting transition, and highest for MgO. "Lower quality" of a Nb film relates to more defects in the crystal structure, which means higher scattering rate and dc resistivity for the metallic state above $T_{c,Nb}$, and following the Ferrell–Glover–Tinkham sum rule,^{72,73} this means reduced superfluid density and longer penetration depth. This expected trend, namely, a decrease in λ_0 with an increase in $T_{c,Nb}$,⁷⁴ is indeed what we find for the data in Table I.

After this correction for the influence of the Nb, the permittivity of the substrate can be calculated with the conformal mapping formula, which gives the results shown in Fig. 4(b). The permittivity of TiO_2 is temperature-independent and the absolute values for the fundamental and highest mode are similar, around 150. Since no temperature dependence is observable, the obtained data can be averaged over the measured temperature range.

In Fig. 5, the permittivities of all measured samples are displayed as a function of the mode number. According to Eq. (1), the mode number directly corresponds to the frequency depending on the dielectric constant of the sample, and therefore, with the upper frequency of 20 GHz in this study and the same resonator geometry for all samples, the number of accessible modes increases with the increase in permittivity.

In contrast to MgO and LaAlO₃, the third studied material, TiO_2 , is anisotropic.^{58,59,75} For this material, measurements were performed with the meander structure of the resonator parallel to the crystalline *a*- or *c*-axis, respectively, and consequently, these experiments yield different absolute values of the permittivity. As expected, for all materials, no temperature or frequency dependence is detected. For the MgO substrate, experimental values for the permittivity between 8 and 10 are found, compared to the literature value of 10.⁵⁶ For the LaAlO₃ substrates, they range between 21 and



FIG. 5. Dielectric constants for the investigated samples, with each resonator operated for several harmonics with different modes *n*. The permittivities are averaged over the measured temperatures (1.4 K–9 K). Depending on the dielectric constant, the mode numbers correspond to frequencies up to 20 GHz.

24, compared to the literature value of 24.⁵⁷ Literature values of the cryogenic GHz permittivity for TiO₂ are reported between 110 and 115 for the crystal a-axis and between 248 and 260 for the c-Here, our experimental values in Fig. 5 also show a clear axis.⁷⁶⁻⁷⁸ difference for the two orientations of the resonator, but the resulting values of 120 and 150 differ less. To explain this, one has to consider the distribution and the direction of the electric field in the coplanar resonator geometry with respect to the crystal axes. For our TiO₂ resonators, the substrate always parallels an *ac*-plane. The microwave electric fields run in the plane perpendicular to the direction of the center conductor in the meander. If the meander is along the TiO₂ c-direction, then the fields are within the tetragonal aaplane of the TiO_2 and thus solely probe the *a*-axis permittivity. If the meander is along an a-direction, then the fields are in an acplane of the TiO₂, and thus, the effective permittivity is a mixture of both *a*-axis and *c*-axis contributions. The situation is complicated further by the turns of the meander structure, where also fields along the otherwise unprobed crystal direction contribute. This could be avoided by using a single straight line as a resonator, but as this also eliminates the bend that defines the length of the coupling arm, then the feedline needs an equivalent bend, making the proper alignment of the two chips even more challenging. If one wants to quantify the contribution of the different crystallographic directions for our present design, then one has to consider the inhomogeneous field distribution in the plane perpendicular to the stripline as well as the field intensity along the differently oriented resonator sections (including the coupling arm and the bends), which depends on the resonator mode. The measurements on TiO2 thus show that one can detect anisotropic dielectric properties with our approach, but due to the non-parallel field distribution of coplanar waveguides and the bends in the center conductor, quantitative analysis is difficult, and thus, other approaches are more favorable to quantify anisotropy.

The resonator quality factors for most of the studied resonators and modes at temperatures below 5 K are in the range between 500 and 5000, with the expected overall decreasing trend with the increase in frequency. In Fig. 4(c), this is shown for various modes of a resonator on TiO₂. The quality factor directly limits the fundamental sensitivity to detect relative changes in ϵ_1 as a function of temperature within one mode, as visible in Fig. 4(b), to roughly 10^{-3} . Comparing different modes and resonators, the error in absolute ϵ_1 typically is a few percent, as evident in Fig. 5. The origin for this larger discrepancy, meaning non-equidistant harmonic resonator frequencies in the experimental data, is not clear, although it has also been observed in previous studies that employ planar cryogenic resonators.

Another key aspect is the coupling of the resonator to the feedline, which should be optimized to not limit Q via coupling losses while keeping high signal for straightforward measurements. Since we want to probe dielectrics of unknown microwave properties, it is difficult to predict the intrinsic resonator losses. Therefore, we have chosen a mounting approach using vacuum grease that is very flexible and allows fast change of resonator coupling by adjusting the distance of the two chips. On the downside, with this technique, it is difficult to control and reproduce the distance on the μ m level that would be desired for the fully optimized coupling. Here, one might consider lithographically patterned spacers⁵² or *in situ* control with cryogenic positioners, but the latter is challenging

V. CONCLUSIONS AND OUTLOOK

This study presents a new resonant approach for characterizing dielectric bulk samples, which is termed distant-flip-chip geometry. With this method, multiple discrete frequencies in the microwave regime up to 20 GHz can be measured. Furthermore, the distant-flip-chip method is compatible with cryogenic temperatures. We use superconducting Nb resonators to ensure optimized measurements since Nb reduces losses at low temperatures and it needs only slight experimental preparations. Furthermore, its properties for microwave resonators are well understood. However, the Nb sputtering was not optimized for these substrate materials.⁴³

Nb as superconducting material limits this approach to temperatures below ≈7 K, and this also holds for another superconductor that has been applied for related experiments and that can be easily deposited, namely Pb.^{81,83,85} As we have shown above, the influence of the temperature-dependent superconducting properties on the resonance frequency can be properly modeled if one can assume that the dielectric under study has little temperature dependence at temperatures near $T_{c,Nb}$. If instead the dielectric has substantial temperature dependence in this range, then the analysis presented above, applying Eq. (3) with fit parameters $v_{0,n}$, λ_0 , and T_c , might not give the appropriate intrinsic material parameters of the Nb, but the fit might subsume the temperature dependence of the dielectric. In this case, an independent measurement of T_c , e.g., from dc resistance or magnetization, can reduce the degrees of freedom of the fit substantially. If the dielectric under study has significant and unknown temperature dependence in the full temperature range, our presented approach can give reliable information below $T_{c,\rm Nb}/2$, as we have recently shown for the quantum paraelectric SrTiO₃.

For several materials with unconventional properties at cryogenic temperatures, such a temperature range might be sufficient, whereas, in general, application at higher temperatures (also higher magnetic fields) is desired. Metallic non-superconducting resonators can be operated up to room temperature and beyond,⁸² but their comparably high intrinsic losses immediately mean reduced sensitivity. Cuprate superconductors with much higher T_c and critical fields than Nb thus could be an attractive alternative,²⁸ but there, the thin-film deposition is much more demanding.

To establish the presented approach, reference measurements on known dielectrics were performed. The samples are between 300 μ m and 500 μ m thickness and the absolute values of the permittivity are between 8 and 160. In addition, anisotropic dielectrics can be characterized, as demonstrated for the case of TiO₂, but with challenges for a full quantitative analysis. The presented approach thus enables GHz dielectric measurements on materials with unknown possibly very high dielectric constant at multiple resonance frequencies and at cryogenic temperatures including mK temperatures in a dilution refrigerator^{53,86} and with only sample requirement, the presence of one large flat sample surface. With this particular combination of accessible parameter regimes, this technique might find unique applications among the various already existing methods for dielectric GHz measurements.

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REFERENCES

¹D. Dimos and C. H. Mueller, Annu. Rev. Mater. Sci. 28, 397 (1998).

² R. Brand, P. Lunkenheimer, and A. Loidl, J. Chem. Phys. **116**, 010386 (2002).

³K. A. Müller and H. Burkard, Phys. Rev. B **19**, 3593 (1979).

⁴H. F. Hess, K. DeConde, T. F. Rosenbaum, and G. A. Thomas, Phys. Rev. B 25, 5578 (1982).

⁵M. Hering, M. Scheffler, M. Dressel, and H. v. Löhneysen, Phys. Rev. B **75**, 205203 (2007).

⁶B. P. Gorshunov, V. I. Torgashev, E. S. Zhukova, V. G. Thomas, M. A. Belyanchikov, C. Kadlec, F. Kadlec, M. Savinov, T. Ostapchuk, J. Petzelt, J. Prokleska, P. V. Tomas, E. V. Pestrjakov, D. A. Fursenko, G. S. Shakurov, A. S. Prokhorov, V. S. Gorelik, L. S. Kadyrov, V. V. Uskov, R. K. Kremer, and

M. Dressel, Nat. Commun. 7, 12842 (2016)

⁷J. Krupka, Meas. Sci. Technol. 17, R55 (2006).

⁸G. Kent, in Proceedings of Conference on Precision Electromagnetic Measurements Digest (IEEE, 1994), pp. 352–353.

⁹J. Krupka, D. Cros, M. Aubourg, and P. Guillon, IEEE Trans. Microwave Theory Tech. 42, 56 (1994).

¹⁰M. V. Jacob, J. Mazierska, K. Leong, and J. Krupka, IEEE Trans. Microwave Theory Tech. **50**, 474 (2002).

¹¹M. S. DiIorio, A. C. Anderson, and B.-Y. Tsaur, Phys. Rev. B 38, 7019 (1988).

¹²S. M. Anlage, H. Sze, H. J. Snortland, S. Tahara, B. Langley, C. B. Eom, M. R. Beasley, and R. Taber, Appl. Phys. Lett. 54, 2710 (1989).

¹³D. E. Oates, A. C. Anderson, C. C. Chin, J. S. Derov, G. Dresselhaus, and M. S. Dresselhaus, Phys. Rev. B 43, 7655 (1991).

¹⁴ B. W. Langley, S. M. Anlage, R. F. W. Pease, and M. R. Beasley, Rev. Sci. Instrum. 62, 1801 (1991).

¹⁵A. Andreone, A. DiChiara, G. Peluso, M. Santoro, C. Attanasio, L. Maritato, and R. Vaglio, J. Appl. Phys. **73**, 4500 (1993).

¹⁶L. Frunzio, A. Wallraff, D. Schuster, J. Majer, and R. Schoelkopf, IEEE Trans. Appl. Supercond. **15**, 860 (2005).

¹⁷G. Hammer, S. Wuensch, M. Roesch, K. Ilin, E. Crocoll, and M. Siegel, Supercond. Sci. Technol. 20, S408 (2007).

¹⁸J. Zmuidzinas, Annu. Rev. Condens. Matter Phys. **3**, 169 (2012).

¹⁹M. Scheffler, K. Schlegel, C. Clauss, D. Hafner, C. Fella, M. Dressel, M. Jourdan, J. Sichelschmidt, C. Krellner, C. Geibel, and F. Steglich, Phys. Status Solidi B 250, 439 (2013).

²⁰W. D. Oliver and P. B. Welander, <u>MRS Bull.</u> 38, 816 (2013).

²¹ M. Scheffler, M. M. Felger, M. Thiemann, D. Hafner, K. Schlegel, M. Dressel, K. S. Ilin, M. Siegel, S. Seiro, C. Geibel, and F. Steglich, Acta IMEKO 4, 47 (2015).
²² N. G. Ebensperger, M. Thiemann, M. Dressel, and M. Scheffler, Supercond. Sci. Technol. 29, 115004 (2016).

²³L. Grünhaupt, N. Maleeva, S. T. Skacel, M. Calvo, F. Levy-Bertrand, A. V. Ustinov, H. Rotzinger, A. Monfardini, G. Catelani, and I. M. Pop, Phys. Rev. Lett. **121**, 117001 (2018).

²⁴J. G. Kroll, F. Borsoi, K. L. van der Enden, W. Uilhoorn, D. de Jong, M. Quintero-Pérez, D. J. van Woerkom, A. Bruno, S. R. Plissard, D. Car, E. P. A. M. Bakkers, M. C. Cassidy, and L. P. Kouwenhoven, *Phys. Rev. Appl.* **11**, 064053 (2019).

²⁵ S. Revenaz, D. E. Oates, D. Labbé-Lavigne, G. Dresselhaus, and M. S. Dresselhaus, Phys. Rev. B 50, 1178 (1994).

²⁶Y. Kubo, F. R. Ong, P. Bertet, D. Vion, V. Jacques, D. Zheng, A. Dréau, J.-F. Roch, A. Auffeves, F. Jelezko, J. Wrachtrup, M. F. Barthe, P. Bergonzo, and D. Esteve, Phys. Rev. Lett. **105**, 140502 (2010).

²⁷ E. F. C. Driessen, P. C. J. J. Coumou, R. R. Tromp, P. J. de Visser, and T. M. Klapwijk, Phys. Rev. Lett. **109**, 107003 (2012).

²⁸A. Ghirri, C. Bonizzoni, D. Gerace, S. Sanna, A. Cassinese, and M. Affronte, Appl. Phys. Lett. **106**, 184101 (2015). ²⁹D. B. Tuckerman, M. C. Hamilton, D. J. Reilly, R. Bai, G. A. Hernandez, J. M. Hornibrook, J. A. Sellers, and C. D. Ellis, Supercond. Sci. Technol. 29, 084007 (2016).

³⁰ M. Thiemann, M. H. Beutel, M. Dressel, N. R. Lee-Hone, D. M. Broun, E. Fillis-Tsirakis, H. Boschker, J. Mannhart, and M. Scheffler, Phys. Rev. Lett. **120**, 237002 (2018).

³¹ F. Levy-Bertrand, T. Klein, T. Grenet, O. Dupré, A. Benoît, A. Bideaud, O. Bourrion, M. Calvo, A. Catalano, A. Gomez, J. Goupy, L. Grünhaupt, U. v. Luepke, N. Maleeva, F. Valenti, I. M. Pop, and A. Monfardini, Phys. Rev. B **99**, 094506 (2019).

³² A. Megrant, C. Neill, R. Barends, B. Chiaro, Y. Chen, L. Feigl, J. Kelly, E. Lucero, M. Mariantoni, P. J. J. O'Malley, D. Sank, A. Vainsencher, J. Wenner, T. C. White, Y. Yin, J. Zhao, C. J. Palmstrøm, J. M. Martinis, and A. N. Cleland, Appl. Phys. Lett. **100**, 113510 (2012).

³³ A. D. O'Connell, M. Ansmann, R. C. Bialczak, M. Hofheinz, N. Katz, E. Lucero, C. McKenney, M. Neeley, H. Wang, E. M. Weig, A. N. Cleland, and J. M. Martinis, Appl. Phys. Lett. **92**, 112903 (2008).

³⁴D. S. Wisbey, M. R. Vissers, J. Gao, J. S. Kline, M. O. Sandberg, M. P. Weides, M. M. Paquette, S. Karki, J. Brewster, D. Alameri, I. Kuljanishvili, A. N. Caruso, and D. P. Pappas, J. Low Temp. Phys. **195**, 474 (2019).

³⁵V. Gupta, B. Yelamanchili, S. Zou, T. Isaacs-Smith, J. A. Sellers, D. B. Tuckerman, and M. C. Hamilton, IEEE Trans. Appl. Supercond. **29**, 1501405 (2019).

³⁶J. Krupka, K. Derzakowski, A. Abramowicz, M. E. Tobar, and R. G. Geyer, IEEE Trans. Microwave Theory Tech. **47**, 752 (1999).

³⁷J. Baker-Jarvis, M. D. Janezic, and J. Krupka, in International Conference on Microwaves, Radar & Wireless Communications (IEEE, 2006), pp. 1093–1096.

³⁸J. Baker-Jarvis, M. Janezic, and D. C. DeGroot, IEEE Instrum. Meas. Mag. 13, 24 (2010).

³⁹N. G. Ebensperger, B. Ferdinand, D. Koelle, R. Kleiner, M. Dressel, and M. Scheffler, Rev. Sci. Instrum. 90, 114701 (2019).

⁴⁰L. Wendel, "Dielectric measurements at GHz frequencies," M.Sc. thesis, University of Stuttgart, 2019.

⁴¹ A. I. Gubin, K. S. Il'in, S. A. Vitusevich, M. Siegel, and N. Klein, Phys. Rev. B 72, 064503 (2005).

⁴²N. Pompeo, E. Silva, S. Sarti, C. Attanasio, and C. Cirillo, Physica C 470, 901 (2010).

⁴³A. Farag, M. Ubl, A. Konzelmann, M. Hentschel, and H. Giessen, Opt. Express 27, 025012 (2019).

⁴⁴D. Bothner, T. Gaber, M. Kemmler, D. Koelle, R. Kleiner, S. Wünsch, and M. Siegel, Phys. Rev. B **86**, 014517 (2012).

⁴⁵J. Goetz, F. Deppe, M. Haeberlein, F. Wulschner, C. W. Zollitsch, S. Meier, M. Fischer, P. Eder, E. Xie, K. G. Fedorov, E. P. Menzel, A. Marx, and R. Gross, J. Appl. Phys. **119**, 015304 (2016).

⁴⁶ M. Göppl, A. Fragner, M. Baur, R. Bianchetti, S. Filipp, J. M. Fink, P. J. Leek, G. Puebla, L. Steffen, and A. Wallraff, J. Appl. Phys. **104**, 113904 (2008).

⁴⁷D. Bothner, C. Clauss, E. Koroknay, M. Kemmler, T. Gaber, M. Jetter, M. Scheffler, P. Michler, M. Dressel, D. Koelle, and R. Kleiner, Appl. Phys. Lett. **100**, 012601 (2012).

⁴⁸D. S. Rausch, M. Thiemann, M. Dressel, D. Bothner, D. Koelle, R. Kleiner, and M. Scheffler, J. Phys. D: Appl. Phys. **51**, 465301 (2018).

⁴⁹Z. K. Minev, K. Serniak, I. M. Pop, Z. Leghtas, K. Sliwa, M. Hatridge, L. Frunzio, R. J. Schoelkopf, and M. H. Devoret, Phys. Rev. Appl. 5, 044021 (2016).

⁵⁰D. Rosenberg, D. Kim, R. Das, D. Yost, S. Gustavsson, D. Hover, P. Krantz, A. Melville, L. Racz, G. O. Samach, S. J. Weber, F. Yan, J. L. Yoder, A. J. Kerman, and W. D. Oliver, npj Quantum Inf. **3**, 42 (2017).

⁵¹ K. J. Satzinger, Y. P. Zhong, H.-S. Chang, G. A. Peairs, A. Bienfait, M.-H. Chou, A. Y. Cleland, C. R. Conner, É. Dumur, J. Grebel, I. Gutierrez, B. H. November, R. G. Povey, S. J. Whiteley, D. D. Awschalom, D. I. Schuster, and A. N. Cleland, Nature 563, 661 (2018).

⁵²K. J. Satzinger, C. R. Conner, A. Bienfait, H.-S. Chang, M.-H. Chou, A. Y. Cleland, É. Dumur, J. Grebel, G. A. Peairs, R. G. Povey, S. J. Whiteley, Y. P. Zhong, D. D. Awschalom, D. I. Schuster, and A. N. Cleland, Appl. Phys. Lett. **114**, 173501 (2019). ⁵³V. T. Engl, N. G. Ebensperger, L. Wendel, and M. Scheffler, arXiv:1911.11456 [cond-mat.supr-con].

⁵⁴R. N. Simons, *Coplanar Waveguide Circuits, Components, and Systems* (Wiley-IEEE Press, 2001).

⁵⁵G. Ghione and C. U. Naldi, IEEE Trans. Microwave Theory Tech. **35**, 260 (1987).

⁵⁶J. Krupka, R. G. Geyer, M. Kuhn, and J. H. Hinken, IEEE Trans. Microwave Theory Tech. 42, 1886 (1994).

⁵⁷T. Konaka, M. Sato, H. Asano, and S. Kubo, J. Supercond. 4, 283 (1991).

58 E. S. Sabisky and H. J. Gerritsen, J. Appl. Phys. 33, 1450 (1962).

⁵⁹R. A. Parker, Phys. Rev. 124, 1719 (1961).

⁶⁰Y. Wiemann, J. Simmendinger, C. Clauss, L. Bogani, D. Bothner, D. Koelle, R. Kleiner, M. Dressel, and M. Scheffler, Appl. Phys. Lett. **106**, 193505 (2015).

⁶¹ The bare feedline chip was measured in the same sample holder as the case with the superconducting resonator, but with the complete sample holder at room temperature. Therefore, the coaxial lines of the sample holder and the coplanar feedline here have higher losses than for the 1.4 K measurement of the resonator. ⁶² M. Scheffler and M. Dressel, Rev. Sci. Instrum. **76**, 074702 (2005).

⁶³L. Ranzani, L. Spietz, Z. Popovic, and J. Aumentado, Rev. Sci. Instrum. 84, 034704 (2013).

64 J.-H. Yeh and S. M. Anlage, Rev. Sci. Instrum. 84, 034706 (2013).

⁶⁵M. Thiemann, "Microwave investigations on superconducting Nb-doped SrTiO₃," Ph.D. thesis, University of Stuttgart, 2018.

⁶⁶F. London and H. London, Proc. R. Soc. London, Ser. A 149, 71 (1935).

⁶⁷M. Tinkham, Introduction to Superconductivity (McGraw-Hill, 1996).

⁶⁸H. A. Wheeler, Proc. IRE **30**, 412 (1942).

⁶⁹C. Kittel, Introduction to Solid State Physics (John Wiley & Sons, Inc., 2005).

⁷⁰The kinetic inductance L_k of a superconductor is proportional to the inverse of the superfluid density and hence proportional to $\lambda^{2,71}$ Our modeling via Eq. (3)

thus describes the temperature-dependent L_k of our resonator, and the rather small difference between measured and corrected data in Fig. 4 indicates that L_k of our transmission is much smaller than its geometric inductance. 46

⁷¹A. J. Annunziata, D. F. Santavicca, L. Frunzio, G. Catelani, M. J. Rooks, A. Frydman, and D. E. Prober, Nanotechnology **21**, 445202 (2010).

⁷² R. A. Ferrell and R. E. Glover III, Phys. Rev. 109, 1398 (1958).

⁷³ M. Tinkham and R. A. Ferrell, Phys. Rev. Lett. 2, 331 (1959).

⁷⁴C. Collignon, B. Fauqué, A. Cavanna, U. Gennser, D. Mailly, and K. Behnia, Phys. Rev. B 96, 224506 (2017).

⁷⁵K. Torokhtii, N. Pompeo, and E. Silva, <u>Meas. Sci. Technol.</u> 25, 025601 (2014).

⁷⁶N. Klein, C. Zuccaro, U. Dähne, H. Schulz, N. Tellmann, R. Kutzner, A. G. Zaitsev, and R. Wördenweber, J. Appl. Phys. **78**, 6683 (1995).

⁷⁷C. Zuccaro, I. Ghosh, K. Urban, N. Klein, S. Penn, and N. M. Alford, IEEE Trans. Appl. Supercond. 7, 3715 (1997).

⁷⁸M. E. Tobar, J. Krupka, E. N. Ivanov, and R. A. Woode, J. Appl. Phys. 83, 1604 (1998).

⁷⁹J. H. Takemoto, F. K. Oshita, H. R. Fetterman, P. Kobrin, and E. Sovero, IEEE Trans. Microwave Theory Tech. **37**, 1650 (1989).

⁸⁰N. Belk, D. E. Oates, D. A. Feld, G. Dresselhaus, and M. S. Dresselhaus, Phys. Rev. B 53, 3459 (1996).

⁸¹D. Hafner, M. Dressel, and M. Scheffler, Rev. Sci. Instrum. 85, 014702 (2014).

⁸²M. Javaheri Rahim, T. Lehleiter, D. Bothner, C. Krellner, D. Koelle, R. Kleiner, M. Dressel, and M. Scheffler, J. Phys. D: Appl. Phys. 49, 395501 (2016).

⁸³M. Thiemann, M. Dressel, and M. Scheffler, Phys. Rev. B **97**, 214516 (2018).

⁸⁴M. Beutel, "Breitbandige ESR-Untersuchungen mit in-situ-Kontrolle von Orientierung und abstand," B.Sc. thesis, University of Stuttgart, 2014.

⁸⁵ M. Köpke and J. Weis, Physica C 506, 143 (2014).

⁸⁶V. Engl, "Planar microwave resonators on SrTiO₃ substrates," M.Sc. thesis, University of Stuttgart, 2019.