Superconducting stripline resonators at frequencies up to 50 GHz for microwave spectroscopy applications

Tobias Wollandt, Markus Thiemann, Martin Dressel, Marc Scheffler

1 Physikalisches Institut, Universität Stuttgart, Stuttgart, Germany
E-mail: scheffl@pi1.physik.uni-stuttgart.de

Abstract. Planar superconducting microwave resonators are commonly operated for various cryogenic applications, typically at frequencies between 2 and 15 GHz. But for certain applications, e.g., microwave spectroscopy to study the dynamics of charges and spins in solids, a wider spectral range is desired. Driving such microwave resonators at higher frequencies is challenging due to enhanced losses and reduced wavelength. Here we present superconducting stripline resonators operating at multiple frequencies as high as 50 GHz. These resonators are fabricated of Pb and can easily be adjusted to particular applications, including mK temperatures in a dilution refrigerator. Demonstrating such a resonator as a spectroscopic tool, we detect the superconducting transition of a Sn sample in a wide spectral range.

1. Introduction
Planar superconducting microwave resonators (based on stripline, microstrip, or coplanar transmission lines [1]) are employed in numerous cryogenic devices that play key roles in e.g., quantum information science [2, 3] or photon detection [4, 5, 6]. A different field of application is microwave spectroscopy on solids: several condensed matter systems that are at the focus of present research have characteristic energy or frequency scales that correspond to the microwave range (GHz frequencies), including conventional [7, 8, 9, 10] and unconventional superconductors [11, 12, 13, 14], strongly correlated metals [15, 16, 17], and magnetic [18, 19] as well as dielectric materials [20]. The energy scales of microwaves correspond to thermal energies of a few K or below ($21 \text{ GHz} \cdot h \approx 1 \text{ K} \cdot k_B$, with Planck constant $h$ and Boltzmann constant $k_B$), and thus microwave spectroscopy studies are particularly suited to probe low-temperature states in solids with similar characteristic energies. Depending on the particular requirements, several different techniques have been developed in recent years to perform microwave spectroscopy at low temperatures. While broadband spectrometers can continuously cover substantial frequency ranges [21, 22, 23, 24, 25], they require elaborate reference or calibration schemes [22, 23, 26, 27], and for many materials of interest they lack the sufficient sensitivity [23]. Cavity resonators on the other hand can be very sensitive [28], but hardly give any information on the frequency dependence. One option to combine high sensitivity with spectral resolution are resonators that can be operated at many different frequencies [29, 30], and one such approach is using stripline resonators [31, 32, 33, 34, 35, 36]. The main advantages of this technique are the compact size...
which is easily compatible with measurements in a dilution refrigerator, the flexible fabrication in terms of resonator frequency, and the option to determine anisotropic material properties [36]. Such stripline resonators are particularly suited to study conductive materials such as metals and superconductors [31, 34, 35, 36, 37, 38], if the intrinsic resonator losses are very small. This requirement can be met for superconducting planar microwave resonators, which can have much higher quality factors than their metallic counterparts [39, 40], but at the expense of somewhat limited temperature and magnetic-field ranges for applications [41, 42, 43, 44].

Most low-temperature experiments with planar microwave devices are performed at frequencies between 2 and 15 GHz, and for certain applications this frequency range is fully sufficient. But in the field of microwave spectroscopy, the materials of interest might require a larger frequency base, and therefore there have been several developments to address a substantially wider spectral range [45, 46, 47], while many microwave spectroscopy setups remain limited to frequencies below roughly 20 GHz. Following the same motivation, in the present work we want to operate superconducting stripline resonators at much higher frequencies than before to make this technique available for microwave spectroscopy in an extended frequency range. Cryogenic microwave experiments quite generally become more challenging at higher frequencies due to the increasing losses in the microwave transmission lines and the larger role of standing waves due to the reduced wavelength. Furthermore, the electrodynamic losses in superconductors strongly increase with frequency [48], and thus the resonance linewidth of superconducting resonators becomes much broader, making the disturbance due to standing waves even more severe. Finally, appropriate cryogenic microwave equipment for higher frequencies is much less available and more costly than lower-frequency equivalents [49].

Figure 1. Measured transmission spectrum of a Pb superconducting stripline resonator at temperature 1.5 K. Numerous resonances are indicated by arrows. The photograph shows such a stripline resonator in its brass mounting.
Figure 2. Microwave performance of a superconducting Pb stripline resonator. (a) The temperature dependence of resonance linewidth (for several modes) is almost flat at low temperature and increases strongly upon approaching $T_{c,Pb} = 7.2 \, \text{K}$. (b) The quality factor $Q$ at higher temperatures exhibits an inverse dependence on frequency as expected for conventional superconductors, whereas at lower temperatures residual losses cause non-monotonic frequency dependence.

2. Experiment
A stripline is a microwave transmission line that consists of a center conductor sandwiched between two dielectric slabs, which in turn are surrounded by conductive ground planes [1]. In our case, the dielectrics are sapphire (127 $\mu$m thick), and all three conductive planes are fabricated of Pb (center conductor 1 $\mu$m thick evaporated film; ground planes bulk foils), which becomes superconducting below $T_{c,Pb} = 7.2 \, \text{K}$ [35, 44]. The meander shape of the center conductor as well as the coupling gaps that define the resonator length (i.e. length of center conductor) and thus the resonator fundamental frequency are created using thermal evaporation through a shadow mask. The resonator components are stacked into purpose-designed brass boxes (see photograph in Fig. 1), which are smaller than those previously used [35]. The resonators are cooled with a $^4$He glass dewar (base temperature 1.5 K), and the microwave signal transmitted through the device is measured with a vector network analyzer.

3. Results
In Fig. 1 we show a typical (uncalibrated) transmission spectrum at base temperature. Clearly, a large number of roughly equidistant, pronounced resonances can be identified as indicated by the arrows. In this case the fundamental frequency is around 1.5 GHz, and higher harmonics throughout the complete spectral range up to 50 GHz can be studied. For such a superconducting resonator, dominant losses stem from thermally excited quasiparticles, and therefore a strong temperature dependence is expected. Such a behavior is indeed found, e.g. in the resonance linewidth, which is determined by fitting the complex transmission coefficient $S_{21}$ (assuming that the parasitic background can be modeled as a complex constant for frequencies near the resonance frequency [30]) and plotted in Fig. 2(a) for numerous resonator modes. As expected, the linewidth increases strongly with temperature when approaching $T_{c,Pb}$. Also, there is the general trend that the resonator linewidth increases with increasing frequency. This behavior is also expected, and its details play an important role concerning the applicability of such resonators as spectroscopic tools for large frequency ranges. To address the frequency
dependence in more detail, in Fig. 2(b) we plot the resonator quality factor \( Q = f_0/\Delta f \), with resonance frequency \( f_0 \) and resonance linewidth \( \Delta f \) for each of the resonant modes, versus frequency (i.e. for all observed modes) for several temperatures. For an ideal superconducting resonator the microwave losses solely depend on the thermally excited quasiparticles. In this case, \( Q \propto f/R_s \propto 1/f \) with frequency \( f \) and surface resistance \( R_s \propto f^2 \) of a superconductor is expected [35]. Indeed, we find this frequency-dependent behavior for temperatures not much lower than \( T_{c,Pb} = 7.2 \text{K} \), as indicated by the dashed line in Fig. 2(b). But at temperatures much lower than \( T_{c,Pb} \), this dependence does not hold any more: here the conduction losses due to quasiparticles are so small that other loss mechanisms become dominant. In particular, residual low-temperature losses that are not well understood [50, 51] and can depend on details of material preparation, resonator geometry etc., and which are regularly found for such resonators [35, 52], have to be taken into account. But more relevant for our applications are the high \( Q \) values that we find at the lowest temperatures throughout our complete spectral range, e.g. \( Q \approx 3500 \) at our highest resonator frequency of 49.32 GHz.

Such high \( Q \) values make these stripline resonators appropriate probes for conductive bulk samples e.g. of unconventional (super-)conductors [34, 35, 36, 53]. To demonstrate such a possible application in spectroscopy, we have replaced one Pb ground plane of such a stripline resonator by a bulk sample of Sn. Again we have measured the resonator properties at cryogenic temperatures, and in Fig. 3 we show the temperature dependence of the linewidth of this Sn-loaded resonator. From Fig. 2 we know that the losses of the Pb are almost temperature independent below 4 K, and right in this regime we now find an abrupt decrease of the resonance linewidth upon cooling, i.e. a clear reduction of microwave losses. We assign this feature to the superconducting transition of the Sn sample [54]. These data demonstrate that the microwave response of a superconducting bulk sample is clearly discernible with a stripline resonator to much higher frequencies than shown previously [35, 53, 55]. Using such resonators for quantitative spectroscopy of samples with unknown microwave properties requires data analysis that can separate the loss contributions of Pb resonator and sample, respectively. In
the simplest case, the total losses of the device (as quantified by $1/Q$ or by resonator linewidth) are governed completely by the sample of interest. This will apply if the sample is metallic and the temperatures of interest are well below $T_{c,Pb}$ [35, 37, 56] or for superconducting samples with $T_c$ below 1 K [36], in particular if their Cooper pair density is rather low and thus their microwave losses are high (compared to other superconductors such as Pb) [53].

4. Conclusions
We have demonstrated superconducting stripline resonators made of Pb with operating frequencies up to 50 GHz. Even for these very high frequencies, quality factors of several thousand are achieved for temperature below 5 K. This substantially extends the frequency range that is accessible for cryogenic applications such as microwave spectroscopy, well beyond the well-established range up to 20 GHz, and we have shown an exemplary application by investigating a Sn bulk sample as a representative for a variety of conductive materials that can now be studied in this wide spectral range.

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