Superconducting coplanar microwave resonators with operating frequencies up to 50 GHz

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Abstract
We demonstrate the operation of superconducting coplanar microwave resonators in a very large frequency range up to 50 GHz. The resonators are fabricated from niobium thin films on sapphire substrates and have fundamental frequencies of 5 GHz or 10 GHz. We study numerous harmonics of the resonators at temperatures between 1.5 K and 6 K, and we determine quality factors of up to 22 600 at 1.5 K. As an example for spectroscopy applications of such resonators we detect the superconducting transition of a bulk tin sample at multiple probing frequencies.

Keywords: microwave resonators, coplanar resonators, superconducting resonators, microwave spectroscopy, superconductivity, Mattis–Bardeen electrodynamics

(Some figures may appear in colour only in the online journal)

1. Introduction

Superconducting coplanar microwave resonators, i.e. sections of a superconducting coplanar waveguide of finite length that are capacitively or inductively coupled to external circuitry, can drastically surpass their metallic equivalents in terms of higher quality factors $Q$, but at the expense of cryogenic cooling [1–4]. Such superconducting coplanar resonators are used for highly sensitive detectors [2, 5–7] and for chip-based quantum information science [3, 8]. Cryogenic microwave studies of material properties also employ planar superconducting resonators: the material under study either constitutes the resonator or is brought close to it [9–14]. There are numerous ongoing efforts to improve the performance of such superconducting resonators, e.g. concerning higher $Q$ [15–18] or reduced susceptibility to magnetic fields [19–22]. Our present work addresses another fundamental aspect, namely the operating frequency of superconducting coplanar resonators, which typically is in the range 1–20 GHz and which we extend to frequencies as high as 50 GHz.

For room-temperature applications there are clear objectives for coplanar resonators at frequencies higher than 20 GHz [23, 24], and there are also perspectives for the cryogenic applications mentioned above: e.g. circuit quantum electrodynamics (circuit QED) at higher resonator frequency could profit from less stringent cooling [25], while facing the downside that operating superconducting resonators at higher frequencies fundamentally restricts $Q$ to lower values due to the strongly frequency-dependent conductivity of superconductors [28]. But the main reasons why so far superconducting coplanar resonators were not reported for frequencies above 20 GHz are more mundane and yet inhibiting. Commercial instruments and components such as amplifiers, circulators, or connectors for frequencies above 20 GHz are much less available and more costly than their lower-frequency counterparts. Furthermore, attenuation in metal-based microwave transmission lines increases strongly with increasing frequency due
to the reduced skin depth [26, 27] as well as due to smaller geometrical cross sections that are required to avoid undesired transmission modes. Finally, standing waves in cryogenic microwave lines caused by partial reflections at discontinuities such as connectors become more difficult to handle due to the smaller wavelength. All these reasons contribute to the present situation that cryogenic microwave experimentation is well established and rapidly growing for low-GHz frequencies, but corresponding works for the 20–50 GHz range are hardly found in the literature. However, in spectroscopy these inconveniences have to be overcome if interesting features of materials under study lie in this particular spectral range, as is often the case for superconducting or correlated materials [28–33]. Also recent developments in quantum information science based on defects in diamond tend towards higher GHz frequencies [34, e.g. considering the SiV defect [35–37].

Optical spectroscopy in the range 20 GHz–100 GHz is extremely demanding as the frequencies are higher than for conventional microwave experiments [38] and too low for far-field THz optics [28, 39, 40], but recently this spectral range has been attacked from the low-frequency side: cryogenic Corbino reflectometry has been extended in frequency [30, 32, 41–43], well beyond the established 20 GHz range [44, 45], and cryogenic broadband coplanar lines were demonstrated even up to 67 GHz [46, 47]. Superconducting planar resonators with their high Q enable much higher sensitivity than these broadband approaches, and when compared to traditional three-dimensional cavities, they are more compact (for operation in dilution refrigerators or magnets) and very flexible concerning choice of multiple operating frequencies [48]. Therefore, we develop and operate superconducting coplanar resonators with frequencies extending up to 50 GHz.

2. Experiment

For this study we used coplanar resonators in a geometry as schematically shown in figure 1(a). The center conductor with width S is separated from the two ground planes by a distance W. The positions of two gaps (of width G) in the center conductor define the length L of the capacitively coupled resonant structure. The resonators were etched into a 200 nm thick niobium film (critical temperature $T_{c,Nb} \approx 8.3$ K for our devices) sputtered onto a 430 $\mu$m thick sapphire substrate, using UV-lithography and a SF$_6$ etching process. Here we show data obtained with two different resonator designs, ‘S20’ and ‘S40’, with fundamental frequencies $f_0 \approx 10$ GHz and 5 GHz, respectively. An overview with relevant resonator parameters is found in table 1.

| Resonator Design | Frequency (GHz) | Q factor |
|------------------|----------------|----------|
| S20              | 10             | 1000     |
| S40              | 5              | 500      |

Each chip (lateral dimensions: 3 mm $\times$ 5 mm) was mounted inside a brass box (outer dimensions: 15.5 mm $\times$ 17 mm $\times$ 8 mm, see figure 1(b)), connected to the external circuitry via two 1.85 mm connectors$^5$, and then cooled in a 4He glass cryostat with base temperature of about 1.5 K. A vector network analyzer (VNA) was used to measure the complex transmission coefficient $S_{21}$. The absolute value $|S_{21}|$ versus frequency $f$ for both resonator types at a temperature of $T = 1.8$ K is shown in figures 1(c) and (d). In both cases the resonances clearly set themselves apart from the background transmission as equally spaced sharp features up to 50 GHz (indicated by arrows). As commonly found for cryogenic microwave experiments, the measured transmission spectra do not only contain the modes of the coplanar resonator, but also a strongly frequency-dependent background due to unwanted cavity modes in the resonator boxes, standing waves and losses in the transmission lines, all of which become more difficult to handle if a microwave experiment is operated at higher frequencies. Full low-temperature calibration of a microwave setup to remove such unwanted influences is demanding [44, 49, 50], and therefore we employ a different approach to separate the desired resonances from the background. As described in [13], we measure the background contribution at a temperature of 10 K, well above $T_{c,Nb}$ of the niobium (i.e. a spectrum that does not contain any resonant modes of the coplanar device because the Ohmic damping in this metallic configuration suppresses them), and we subtract this spectrum from the transmission spectra below $T_{c,Nb}$ as complex quantities.

3. Resonator performance

As an example, figures 2(a) and (b) show the temperature dependence of the third mode of an ‘S40’ resonator (fundamental frequency 5 GHz) before and after subtraction of the background, respectively, where most of the distortions of the measured resonator spectrum are removed by the subtraction.

Concerning the absolute values of the quality factor, which are listed in table 2 for our lowest temperature of 1.5 K, a strong frequency dependence is expected: with increasing frequency, the conductivity of a superconductor strongly decreases and the surface resistance increases [13, 28, 51], leading to decreasing intrinsic $Q$, and also the capacitive coupling to the feedlines, which can be designed to balance low external losses versus measurable signal strength, contributes [3]. Furthermore, the microwave losses of superconductors at lowest temperatures are often governed by residual losses [52] that are not well understood and that for our designs often depend on frequency in an uneven fashion, possibly because the field distributions of the different modes differ

$^4$ Concerning coaxial cables, many cryogenic microwave setups are already equipped with semirigid cables of 2.2 mm outer diameter (0.086 inch standard) that allow moding-free operation up to 67 GHz.

$^5$ Type V102F-R connectors by Anritsu.
in sensitivity concerning the defects e.g. in the bends of the center-conductor meander structure. Undesired coupling to parasitic resonance modes within the resonator assembly also contributes to pronounced non-monotonic frequency dependence of the measured $Q$ and impedes quantitative analysis in terms of intrinsic materials properties. Regardless of these undesired loss contributions, our data demonstrate that $Q$ above $10^4$ can be achieved for frequencies well beyond 30 GHz.

Figure 2(d) shows the temperature dependence of the resonance frequencies $f_0(T)$ for the same resonator, each normalized to the resonance frequency $f_{0,1.5\text{K}}$ at the lowest temperature. The shift in resonance frequency is caused by the change in penetration depth of the niobium, which in turn is governed by the temperature-dependent Cooper-pair density. The full lines in figure 2(d) are calculated using the Mattis–Bardeen formalism [28, 53]: with $T_{c,Nb} = 8.3$ K, gap-to-$T_c$ ratio $\Delta_{0,Nb}/(k_B T_{c,Nb}) = 1.97$ (consistent with Nb literature [56, 59]); with Boltzmann constant $k_B$, and the frequencies of the experiment as input parameters (and additionally the static case of zero frequency), the temperature dependence of the normalized surface impedance is calculated, which then determines the temperature dependence of the normalized resonator frequencies. For $s$-wave superconductors the temperature dependence of the penetration depth should be flat at low $T$ [54, 55] and frequency independent for $hf \ll 2\Delta$ with optical energy gap $2\Delta$ and Planck constant $h$. In the case of niobium with $2\Delta_0 = 2\Delta(T = 0) \approx 720$ GHz [56], this condition is met even for our highest accessible frequencies, but only at temperatures well below $T_{c,Nb}$. With increasing temperature, we observe a spreading of the experimental data for the different frequencies that is consistent with the theoretical expectations.

4. Application: probing a bulk superconductor

The data presented so far only consider the microwave properties of the bare resonators. The high quality factors as well as the only weak temperature dependences of quality factor and resonance frequencies at low temperatures make these resonators a promising spectroscopic tool to investigate the optical properties of different solids in the microwave regime. Possible field of application could be the study of samples with intrinsic energy scales below 50 GHz, such as heavy-fermion systems, where the scattering rate of the quasiparticles shifts into the microwave regime at low temperatures [12, 30] or systems, where the scattering rate of the quasiparticles shifts into the microwave regime at low temperatures [12, 30] or superconductors with a transition temperature below 1 K, as the only weak temperature dependences of quality factor and resonance frequencies at low temperatures make these resonators a promising spectroscopic tool to investigate the optical properties of different solids in the microwave regime.

Figure 2(d) shows the temperature dependence of the quality factor $Q$ of this sample-loaded resonator is shown in figure 3(a). For temperatures $T > 3.8$ K the quality factor shows a temperature dependence originating from the temperature-dependent...
response of the niobium resonator, whereas the tin sample is temperature-independent in this regime. Upon cooling below $T = 3.8$ K an abrupt rise in quality factor is observable originating from the tin sample entering the superconducting phase [60]. This transition is seen up to a frequency of 48.72 GHz, thus proving the interaction of the applied microwaves and the sample at these high frequencies. Figure 3(b) shows the response of the niobium resonator, whereas the tin sample is temperature-independent in this regime. Upon cooling below $T = 3.8$ K an abrupt rise in quality factor is observable originating from the tin sample entering the superconducting phase [60]. This transition is seen up to a frequency of 48.72 GHz, thus proving the interaction of the applied microwaves and the sample at these high frequencies. Figure 3(b) shows the

The slight deviation between our measured $T_{\text{c},\text{Sn}}$ of tin and the literature value might be due to an error in the temperature measurement.

Table 2. Quality factor $Q$ of ‘S40’ coplanar resonator at $T = 1.5$ K for the modes shown in figure 2(c).

| Mode number | Mode frequency (GHz) | $Q$ at 1.5 K |
|-------------|----------------------|--------------|
| 2           | 9.95                 | 4210         |
| 3           | 14.85                | 17000        |
| 4           | 19.75                | 1480         |
| 6           | 29.40                | 22600        |
| 7           | 34.23                | 14200        |
| 8           | 39.04                | 6980         |
temperature dependence of the resonator bandwidth $f_B$, with the bandwidth $f_{B;1.6\ K}$ at lowest temperature subtracted, for the same resonator modes as in figure 3(a). If the resonator losses are dominated by conductive elements, then their surface resistance $R_s$ is proportional to $f_B - f_{B;1.6\ K}$ and can be calculated via cavity perturbation theory [61], but requires detailed knowledge of the microwave field geometry with respect to the sample. Therefore, we resort to a more qualitative evaluation of these data: optical properties of superconductors are treated within the Mattis–Bardeen theory [53, 62], and our observed temperature dependence in figure 3(b) qualitatively matches expectations as shown in the inset of figure 3(b). Here the effective overall surface resistance $R_{s,\comb}$ was calculated assuming a BCS-type temperature dependence of the superconducting energy gaps [63] for tin and niobium (assuming $T_{c,\Sn} = 3.8$ K and $\Delta_{0,\Sn}/(k_B T_{c,\Sn}) = 1.76$ for tin and respective values for niobium as above) and a 0.1% contribution of the Sn sample to the total response of the resonator. A fully quantitative analysis of our data will require more detailed consideration of the microwave field distribution, which is not a plain coplanar structure any more due to the presence of the conducting sample. Furthermore, future refining of the distance between conductive sample and superconducting coplanar resonator will allow improved sensitivity to the high-frequency sample response. Still, the present data clearly demonstrate that the electrodynamics of a sample under study, in this case superconducting tin, can be probed with superconducting coplanar resonators at frequencies up to 50 GHz.

5. Conclusions

Using microwaves in transmission we have shown that superconducting coplanar resonators are well suited for operating frequencies up to 50 GHz. We did not yet optimize the resonators in terms of losses but we rather focused on ease of use concerning our particular motivation of spectroscopy. Therefore,
our strategy is operating resonators with fundamental frequencies of 5 GHz or 10 GHz at multiple harmonics up to the 50 GHz limit that was set by the employed VNA. (We expect that similar operation up to the 67 GHz limit of the 1.85 mm connectors can be achieved with a VNA covering those frequencies.) Optimizing a coplanar resonator for harmonics that differ in frequency by a factor of ten is difficult, in particular concerning the appropriate choice of resonator coupling as well as the presence of parasitic resonance modes. If instead one is interested in a single-frequency coplanar resonator for 50 GHz operation, then one will probably choose this frequency as fundamental mode. The corresponding shorter resonator length allows a substantially smaller chip size, which can suppress parasitic resonances for this frequency range. Considering our present, not-yet-optimized resonator design status, it is not surprising that we observed quality factors that are lower than those that were demonstrated with optimized planar superconducting resonators at frequencies below 10 GHz [15, 18], and we expect that substantial increases in quality factors can be achieved with modified designs. But already at this stage we have demonstrated throughout our very wide frequency range quality factors that clearly surpass their non-superconducting counterparts [4]. Microwave frequencies well above 20 GHz are thus now available for sensitive spectroscopy studies with compact resonator designs as well as for on-chip quantum optics, and cryogenic experiments that are commonly performed at a few GHz can now be extended to much higher frequencies. On the one hand this allows spectroscopic studies of intrinsic energy scales that were previously not accessible (e.g. in superconductors [57, 58] and correlated metals [12]), and on the other hand, for broadband phenomena (e.g. dissipation in two-level systems that is studied from both a fundamental and an applied point of view [64–66]) one can reach the regime where photon energy exceeds thermal energy already at $^4$He temperatures.

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