### Stripline resonators for cryogenic microwave spectroscopy on metals and superconductors

Marc Scheffler, Christian Fella, and Martin Dressel
1. Physikalisches Institut, Universität Stuttgart, D-70550 Stuttgart, Germany
E-mail: scheffl@pi1.physik.uni-stuttgart.de

**Abstract.** Microwave spectroscopy is a powerful experimental tool to study the electrodynamics of metals and superconductors at comparably low frequencies. To overcome some disadvantages of the established cryogenic microwave techniques, we use stripline resonators as a probe where the bulk sample under study represents one of the ground planes of the transmission line. We discuss striplines made of copper as well as superconducting lead, and we show the applicability of this technique with measurements at the superconducting transition of a bulk sample of tantalum.

### 1. Introduction

Microwave spectroscopy gives experimental access to the dynamics of low-energy excitations of solids.[1] One goal here is to obtain information in a large frequency range to address all relevant energy scales as well as broad spectral features. In recent years, broadband microwave experiments at temperatures below 10 K have proven to be particularly helpful to study the charge dynamics and excitations of conventional[2] and exotic superconductors[3] and of strongly correlated metals.[4]

The established techniques of cryogenic microwave spectroscopy all have certain fundamental advantages and disadvantages: cavity resonators are very sensitive to relative changes of the microwave properties of a sample, but they are usually limited to a single frequency (i.e. give no spectral information).[1] The bolometric approach is both very sensitive and broadband, but it cannot reveal information about the phase of the microwave response.[5] Reflection measurements in Corbino geometry are broadband[6] and give the full phase information, but the sensitivity is limited.[7] and here the study of metals and superconductors is only possible if the samples are thin films, ideally structured as a strip.[8] For many strongly correlated metals and superconductors, thin films are not available, in contrast to high-quality single crystals. The goal of the present study is to develop an experimental technique to study bulk samples of metals and superconductors at cryogenic temperatures to access their microwave conductivity over an extended frequency range.

### 2. Concept

In the present study we employ stripline resonators as microwave probes. The general layout of our stripline resonators is shown in Fig. 1: a conducting strip as inner conductor is surrounded by two parallel, outer conducting planes which act as ground for the transmission line. Inner conductor and ground planes are separated by a dielectric. The dimensions of strip and dielectric
Figure 1. Scheme of stripline resonator. Half of upper dielectric and sample are removed for clarity; hidden rear parts are symmetric to those in the front. Gaps in the center conductor define resonator length and capacitively couple the resonator with the feed lines.

are designed to match the conventional characteristic impedance of microwave electronics, $Z_0 = 50\,\Omega$.\cite{9} To transform a planar transmission line into a microwave resonator, two gaps are introduced into the inner conductor; here the microwave signal is reflected, and the standing wave pattern between the two gaps leads to transmission resonances when the distance between the two gaps is a multiple of half the wavelength. We explicitly utilize several harmonics of the resonator to access the frequency-dependent response of the sample.

To allow the study of bulk samples, the sample acts as one of the ground planes of the transmission line, and thus contributes to the overall losses and phase shift of the transmission line, which can be accessed via the resonator properties. Such an experimental approach has been previously employed to study the microwave properties of superconducting thin films.\cite{10, 11, 12} In recent years, coplanar resonators instead of stripline or microstrip resonators have become increasingly popular for cryogenic microwave experiments due to the convenient fabrication and control of microwave properties.\cite{13} but since we explicitly want to work with bulk samples, we cannot take that route.

Quantitative analysis is easier if the sample introduces the dominant resonator losses compared to the other relevant loss contributions: the coupling losses can be reduced by choosing a weak coupling, but in that case the transmission signal will be reduced. Dielectric losses usually can be neglected compared to the conduction losses if the stripline is manufactured from a low-loss material, in our case teflon or sapphire. The conduction losses, on the other hand, constitute a more severe contribution: because of the small cross section of the center conductor, the relative losses are much higher here than in the ground planes. To reduce the loss contribution of the center conductor (and the second ground plane), we choose highly conductive materials, namely copper and superconducting lead.

To cover a broad frequency range, the frequency of the fundamental mode should be as low and the resonator as long as possible. In practice, one limiting factor is the size of the sample: the sample should cover the complete resonator. Typical sample size for single crystals is several millimeters in diameter. To fit as long a resonator as possible into this area, we use a meander shape for the center conductor.\cite{10, 11, 12, 13}

3. Experiment

In the present study, we compare two types of resonators: the first one is fabricated from a commercial microwave laminate,\cite{14} i.e. the dielectric is based on teflon, and the center conductor and the non-sample ground plane are made of thick layers of copper. The advantages of this approach are simple and fast fabrication, ruggedness of the resonator, and a wide accessible temperature range. Typical transmission data of such a resonator are shown in Fig. 2(a). Clearly there are several resonances accessible, with quality factor $Q$ of approximately 200 at a temperature of 15 K.

The second type of resonators is made of superconducting lead. Superconducting resonators have much lower losses than metallic ones, but they can only be operated below the critical
Figure 2. Transmission spectra of a copper resonator at 15 K (a) and a lead resonator at 1.2 K (b). Inset of (b) shows the frequency dependence of the quality factor $Q$ for the lead resonator.

temperature $T_c$ of the superconductor. Here we have chosen lead as superconducting material because its $T_c = 7.2$ K is comparably high for an elemental superconductor and because it can easily be deposited as a thin film using a thermal evaporator. To generate the center conductor and its meander structure, the lead was deposited through a shadow mask. Transmission spectra of a superconducting lead resonator at 1.2 K are shown in Fig. 2(b). Due to the frequency dependence of the microwave conductivity in the superconducting state,[1, 2] $Q$ for the different resonance frequencies of the lead resonator roughly behaves as the inverse of frequency as shown in the inset of Fig. 2(b), exceeding 9000 for 1.5 GHz.

After comparing these two types of resonators, we have chosen to use superconducting resonators despite their limited temperature range: their superior $Q$ leads to a much better sensitivity, and for several material classes of current research the interesting physics takes place mostly at low temperatures.

As one of our test measurements, we present data obtained on a bulk sample of tantalum. Tantalum is a superconductor which was recently considered for certain microwave applications[15] and whose $T_c = 4.5$ K is conveniently located between the $T_c$ of the lead resonators and the lowest temperatures accessible with our $^4$He cryostats. The $Q$ of a lead stripline resonator with a tantalum sample is shown in Fig. 3 for the first four modes of the resonator and for temperatures between 1.2 K and 8 K. Clearly, there are two temperatures where $Q$ changes drastically: above 7.2 K, $Q$ is low and governed by the losses in the lead center conductor, which is a normal metal. Below 7.2 K the lead becomes superconducting, and its losses are reduced drastically; as a result $Q$ increase substantially to an almost frequency-independent value of roughly 2500: now the losses of the metallic tantalum ground plane dominate the losses. Below 4.3 K the tantalum is superconducting, and we find high $Q$ values and a frequency dependence similar to the all-lead resonator presented in Fig. 2(b). Thus we can clearly observe at GHz frequencies the superconducting transition of a bulk sample which is part of a stripline resonator. Furthermore, in the normal state of the tantalum sample, its metallic losses dominate the overall losses of the resonator, which demonstrates that this experimental approach is appropriate to study the microwave properties of conductive bulk samples.
4. Outlook

After our successful test measurements, experiments on single crystals of other metals, in particular strongly correlated materials, are now feasible. But there still remain several technical aspects which we should improve: for the superconducting resonators, only resonances at frequencies below 10 GHz could be observed consistently so far. This frequency range should be increased to at least 20 GHz; if this turns out to be experimentally challenging with a resonator of fundamental frequency around 1 GHz, we might have to use several resonators of different fundamental frequencies. Also we will try different superconductors for the resonators, such as niobium with its even higher $T_c$ compared to lead.

Acknowledgements

We thank Gabriele Untereiner and Günther Klein for sample preparation, Conrad Clauß and Katrin Steinberg for experimental support, Rainer Schulze Höing for the laminates, and we acknowledge financial support by the DFG, including SFB/TRR21.

References

[1] Dressel M and Grüner G 2002 Electrodynamics of Solids (Cambridge: Cambridge University Press)
[2] Steinberg K, Scheffler M and Dressel M 2008 Phys. Rev. B 77 214517
[3] Turner P J, Harris R, Kamal S, Hayden M E, Broun D M, Morgan D C, Hosseini A, Dosanjh P, Mullins G K, Preston J S, Liang R, Bonn D A and Hardy W N 2003 Phys. Rev. Lett. 90 237005
[4] Scheffler M, Dressel M, Jourdan M and Adrian H 2005 Nature 438 1135
[5] Turner P J, Broun D M, Kamal S, Hayden M E, Bobowski J S, Harris R, Morgan D C, Preston J S, Bonn D A and Hardy W N 2004 Rev. Sci. Instrum. 75 124
[6] Booth J C, Wu D H and Anlage S M 1994 Rev. Sci. Instrum. 65 2082
[7] Scheffler M and Dressel M 2005 Rev. Sci. Instrum. 76 074702
[8] Scheffler M, Kilic S and Dressel M 2007 Rev. Sci. Instrum. 78 086106
[9] Pozar D M 1998 Microwave Engineering (New York: John Wiley & Sons)
[10] Dilorio M S, Anderson A C and Tsaur B-Y 1988 Phys. Rev. B. 38 7019
[11] Oates D E, Anderson A C, Chin C C, Derov J S, Dresselhaus G and Dresselhaus M S 1991 Phys. Rev. B. 43 7655
[12] Revenaz S, Oates D E, Labbé-Lavigne D, Dresselhaus G and Dresselhaus M S 1994 Phys. Rev. B. 50 1178
[13] Göppl M, Fargner A, Baur M, Bianchetti R, Filipp S, Fink J M, Leek P J, Puebla G, Steffen L and Wallraff A 2008 J. Appl. Phys. 104 113904
[14] RT/duroid® 5880 by Rogers Corporation
[15] Barends R, Baselmans J J A, Hovenier J N, Gao J R, Yates S J C, Klapwijk T M and Hoovers H F C 2007 IEEE Trans. Appl. Supercond. 17 263