

Niobium stripline resonators for microwave studies on superconductors

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Abstract. Microwave spectroscopy is a powerful experimental tool to reveal information on the intrinsic properties of superconductors. Superconducting stripline resonators, where the material under study constitutes one of the ground planes, offer a high sensitivity to investigate superconducting bulk samples. In order to improve this measurement technique, we have studied stripline resonators made of niobium, and we compare the results to lead stripline resonators. With this technique we are able to determine the temperature dependence of the complex conductivity of niobium and the energy gap $\Delta(0) = 2.1$ meV. Finally we show measurements at the superconducting transition of a tantalum bulk sample using niobium stripline resonators.

1. Introduction

Optical spectroscopy on metals and superconductors can reveal information about charge carrier dynamics as well as electromagnetic excitations [1]. In the case of superconductors and correlated metals, these are connected to low energy scales both in temperature and in frequency and therefore have to be probed with low-energy optics, i.e. in the THz and GHz ranges [2]. Obtaining spectral information on highly conductive materials at cryogenic temperatures in the microwave range has proven technically challenging. While broadband measurements on a number of superconductors [3–7] have successfully been performed on thin films using Corbino spectrometers [8–10] or on single crystals using a bolometric approach (without obtaining phase information) [11–13], there is so far no experimental technique that allows broadband, phase-sensitive measurements on low-loss bulk samples. Therefore, in recent years new techniques have been developed that are resonant in nature, thus are very sensitive to small losses in bulk samples, and at least give certain information about the frequency-dependent response by operating at several resonant frequencies [2, 14, 15]. Our approach is based on superconducting striplines where the sample of interest replaces one of the ground planes [16]. So far, our striplines were made of Pb thin films [17, 18]. In the present work, we



investigate in which regard Nb thin films can also be employed for this purpose and whether their performance can even surpass that of the Pb films.

2. Experiment

The stripline is a layered structure, consisting of the center strip sandwiched between two dielectric plates and two conducting ground planes (see Fig. 1(a)). In case of the Nb stripline

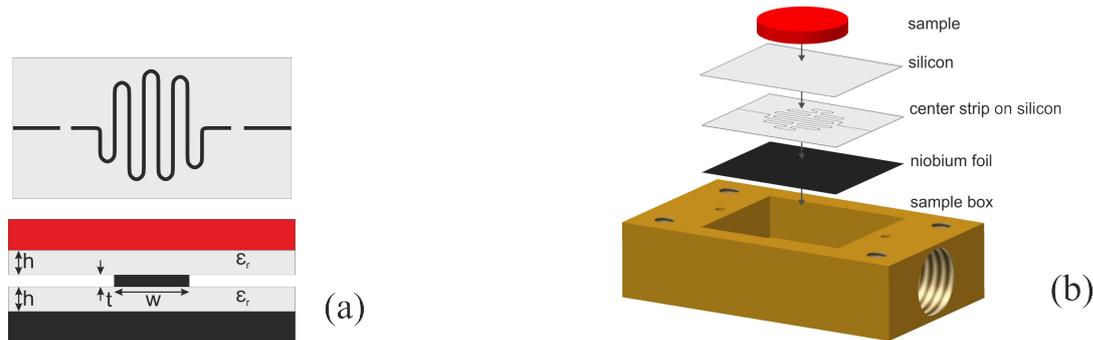


Figure 1: (a) Top: Top view on the meandered center strip with the gaps. Bottom: Cross section of a stripline. The characteristic impedance of a stripline is a function of height h of the dielectric planes, width w and height t of the center strip and the dielectric constant ϵ_r of the dielectric [19]. (b) Assembly of the stripline resonator into the brass sample box.

resonators, two $100\ \mu\text{m}$ thin $12 \times 10\ \text{mm}^2$ silicon plates were used as a dielectric, with a resistivity $>5000\ \Omega/\text{cm}$, due to the low dielectric losses and high dielectric constant [20] and $8\ \mu\text{m}$ thick Nb foils as ground planes. Nb ($T_c=9.2\ \text{K}$) was used as the conductor material instead of the previously used Pb ($T_c=7.2\ \text{K}$) due to the higher transition temperature. The center strip was fabricated by sputtering Nb onto one of the silicon plates, followed by optical lithography and SF_6 etching. Due to two $80\ \mu\text{m}$ gaps in the center conductor the stripline becomes a resonant structure. Since the frequency of the fundamental mode depends on the length of the stripline section between the gaps, the center strip was meander-shaped as shown in Fig. 1(a) to achieve resonance frequencies as low as possible for a given sample size. The stripline resonator was mounted inside a brass box and connected via coaxial microwave connectors to the $50\ \Omega$ measurement circuitry (see Fig. 1(b), [17]). By replacing one ground plane by any conducting sample, it is possible to determine the frequency and temperature dependence of the surface resistance R_s and the penetration depth λ of the sample [17]. In the present study all-Nb resonators and Nb resonators loaded with a tantalum sample were investigated in a temperature range between $1.6\ \text{K}$ and $9.2\ \text{K}$.

3. Results

3.1. All-Nb resonator

In Fig. 2(a) the frequency dependence of R_s (obtained for 6 resonances at frequencies between $1.5\ \text{GHz}$ and $11\ \text{GHz}$) of an all-Nb resonator is compared to R_s of an all-Pb resonator. Both show a quadratic frequency dependence in accord with theoretical predictions [21]. Surprisingly R_s of the Nb remains in the same order of magnitude as that of the Pb, despite the

higher T_c . It has already been shown that defects on the resonator surface can increase R_s [22]. Therefore microscopic non-superconducting defects in the sputtered center strip may be an explanation for the higher R_s [23]. The measured temperature dependence of the resonance

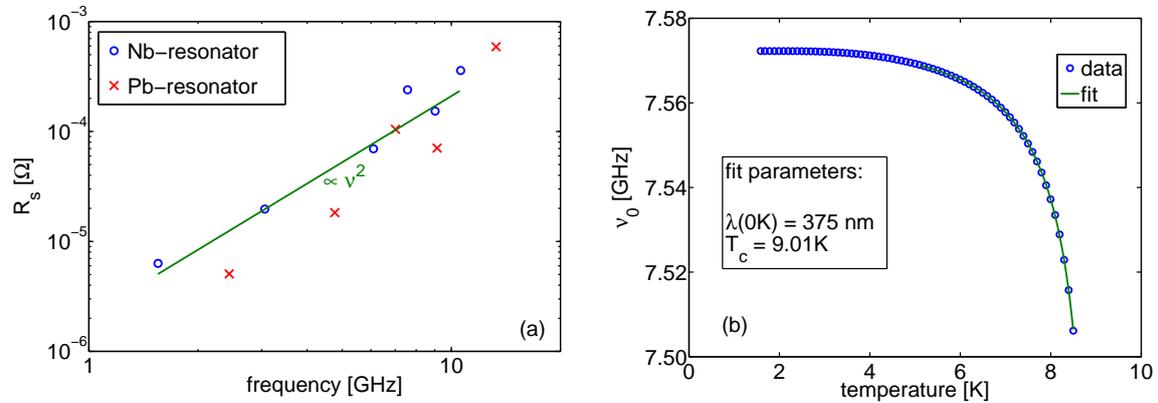


Figure 2: (a) Frequency dependence of R_s of Nb and Pb at $T = 1.6$ K. Despite the higher T_c , Nb shows a higher R_s . (b) Temperature dependence of the resonance frequency of the 5th mode. The green line represents a fit from which $\lambda(0K)$ and T_c can be determined as described in [17].

frequency is shown in Fig. 2(b). The drop of ν_0 towards higher temperatures is due to the Nb entering the normal conducting state. The temperature dependence of ν_0 gives access to the penetration depth $\lambda(0K) \approx 377$ nm and from that the imaginary part of the impedance X_s can be determined [1]. In Fig. 3(a) the temperature dependence of the impedance is shown. The complex conductivity $\hat{\sigma} = \sigma_1 + i\sigma_2$ can now be calculated from the complex impedance [1].

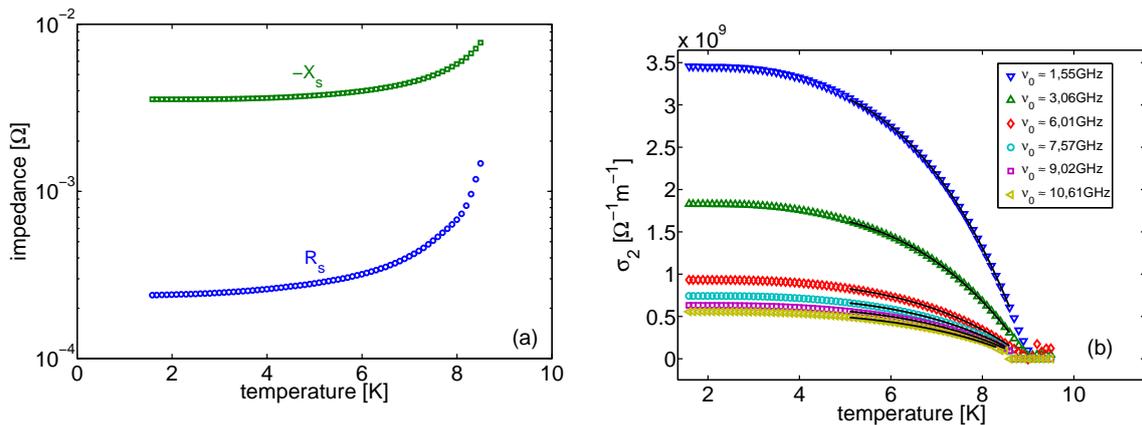


Figure 3: (a) Temperature dependence of the real and imaginary parts of the complex impedance of a pure Nb resonator obtained from the 5th mode. (b) Temperature dependence of the imaginary part σ_2 of the complex conductivity obtained from the fundamental mode and higher harmonics. The black lines represent fits of Eq. (1).

Fig. 3(b) shows the temperature dependence of the imaginary part σ_2 of the conductivity, which is connected to the superconducting energy gap Δ via:

$$\frac{\sigma_2(T)}{\sigma_n} \approx \frac{\pi\Delta(T)}{\hbar\omega} \tanh\left(\frac{\Delta(T)}{2k_B T}\right) \quad (1)$$

By using the high temperature approximation $\Delta(T) \approx \Delta(0K)\sqrt{3.016\left(1 - \frac{T}{T_c}\right) - 2.4\left(1 - \frac{T}{T_c}\right)^2}$ [24], Eq. (1) can be fitted to the measured data with the fit parameters $\Delta(0K)$, T_c , and the real part σ_n of the conductivity in the normal conducting state. Averaging $\Delta(0K)$ obtained from all measured modes gives a value of 2.1 meV or $2\Delta(0K) = 5.3k_B T_c$. The energy gap of Nb thin films has already been investigated with THz-spectroscopy and a value of $2\Delta(0) = 4.1k_B T_c$ was observed [25]. Both studies show deviations from the weak coupling BCS limit ($2\Delta(0K) = 3.5k_B T_c$ [26]) and may indicate a strong electron-phonon interaction.

3.2. Nb resonator loaded with tantalum sample

As a further test measurement we present data obtained from a bulk tantalum sample. Tantalum has a suitable $T_c = 4.5$ K which lies between the transition temperature of the Nb resonators and the lowest temperature accessible with our ^4He cryostat. Fig. 4(a)

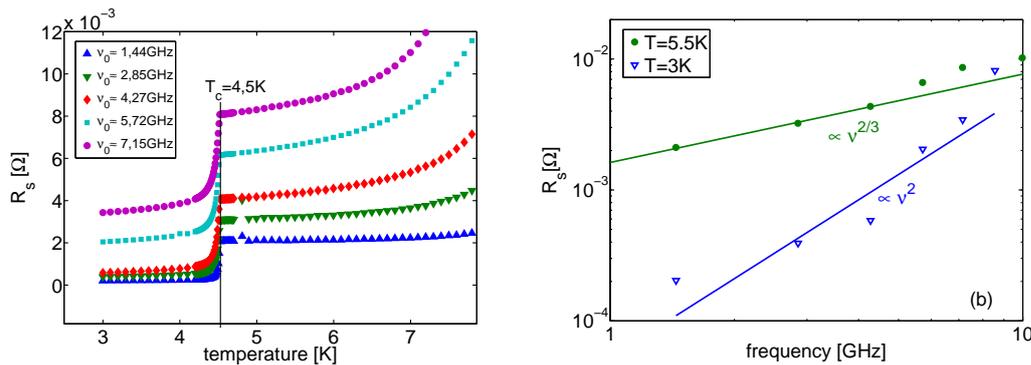


Figure 4: (a) Temperature dependence of R_s of tantalum for several modes. The drop in R_s at 4.5 K is due to the tantalum entering the superconducting state. (b) Frequency dependence of R_s of tantalum in the metallic and superconducting states. Lines are guides to the eye, representing $\nu^{2/3}$ and ν^2 dependencies.

shows the temperature dependence of R_s of the tantalum sample obtained from the different modes. Clearly a drop in R_s is visible at 4.5 K, which is due to the tantalum entering the superconducting state. At a temperature of 5.5 K tantalum is in the metallic state and R_s shows a frequency dependence of $R_s(\nu) \propto \nu^{2/3}$, which indicates that the tantalum is in the anomalous skin effect regime (see Fig. 4(b)) [17]. At 3 K the tantalum sample has entered the superconducting state, and a clear change in the frequency dependence is visible.

4. Conclusions and outlook

Using Nb as a superconducting material for stripline resonators, we increased the upper limit of the measurable temperature range from 6 K to 8 K, but a lower R_s was not achieved.

Future optimization in film growth might reduce the surface impedance and then allow even more sensitive measurements on low-loss bulk superconductors. In contrast to the previous studies using Pb resonators [17], Nb is a type-II superconductor that might allow operation in higher magnetic fields. This might be aggravated by field-dependent microwave losses due to vortices, but strategies to overcome these problems are being developed [27,28]. The test measurements on superconducting tantalum prove the applicability of our technique. Since our approach can easily be implemented in a dilution refrigerator, microwave studies on a number of exotic superconductors, e.g. heavy-fermion superconductors [2,29] or Sr₂RuO₄ [15] now become feasible.

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References

- [1] Dressel M and Grüner G 2002 *Electrodynamics of Solids* (Cambridge: Cambridge University Press)
- [2] Scheffler M et al 2013 *Phys. Status Solidi B* **250**, 439
- [3] Wu D H, Booth J C and Anlage S M 1995 *Phys. Rev. Lett.* **75** 525
- [4] Ohashi T, Kitano H, Maeda A, Akaike H and Fujimaki A 2006 *Phys. Rev. B* **73** 174522
- [5] Steinberg K, Scheffler M and Dressel M 2008 *Phys. Rev. B* **77** 214517
- [6] Pompeo N, Silva E, Sarti S, Attanasio C and Cirillo C 2010 *Physica C* **470** 901
- [7] Liu W, Kim M, Sambandamurthy G and Armitage N P 2011 *Phys. Rev. B* **84** 024511
- [8] Booth J C, Wu D H and Anlage S M 1994 *Rev. Sci. Instrum.* **65** 2082
- [9] Scheffler M and Dressel M 2005 *Rev. Sci. Instrum.* **76** 074702
- [10] Steinberg K, Scheffler M and Dressel M 2012 *Rev. Sci. Instrum.* **83** 024704
- [11] Turner P J et al 2003 *Phys. Rev. Lett.* **90** 237005
- [12] 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
- [13] Bobowski J S et al 2010 *Phys. Rev. B* **82** 094520
- [14] Huttema W A, Morgan B, Turner P J, Hardy W N, Zhou X, Bonn D A, Liang R and Broun D M 2006 *Rev. Sci. Instrum.* **77** 023901
- [15] Ormeno R J, Hein M A, Barraclough T L, Sibley A, Gough C E, Mao Z Q, Nishizaki S and Maeno Y 2006 *Phys. Rev. B* **74** 092504
- [16] DiIorio M S, Anderson A C and Tsaur B-Y 1988 *Phys. Rev. B* **38** 7019
- [17] Hafner D, Dressel M and Scheffler M 2014 *Rev. Sci. Instrum.* **85** 014702
- [18] Scheffler M, Fella C and Dressel M 2012 *J. Phys. Conf. Ser.* **400** 052031
- [19] Wheeler H A 1978 *IEEE Transactions on Microwave Theory and Techniques* **26** pp 866-76
- [20] Krupka J, Breeze J, Centeno A, Alford N, Claussen T and Jenson L 2006 *IEEE Transactions on Microwave Theory and Techniques* **54** pp 3995-4001
- [21] Halbritter J 1974 *Zeitschrift für Physik* **266** pp 209-17
- [22] Pierce J M 1973 *Journal of Applied Physics* **44** pp 1342-7
- [23] Benvenuti C, Calatroni S, Darriulat P, Peck M A, Valente A-M and Van't Hof C A 2001 *Physica C* **351** pp 421-8
- [24] Ferrell R A 1964 *Zeitschrift für Physik* **182** 1
- [25] Pronin A V, Dressel M, Pimenov A, Loidl A, Roshchin I V and Greene L H 1998 *Phys. Rev. B* **57** 14416
- [26] Buckel W, Kleiner R 2004 *Superconductivity Fundamentals and Applications* (Wiley-VCH Verlag GmbH)
- [27] Bothner D, Gaber T, Kemmler M, Koelle D, Kleiner R 2011 *Appl. Phys. Lett.* **98** 102504
- [28] Bothner D et al 2012 *Appl. Phys. Lett.* **100** 012601
- [29] Truncik C J S et al 2013 *Nature Commun.* **4** 2477