NEW EXPERIMENTAL RESULTS FOR MICROWAVE CONDUCTIVITY OF HIGH-TC SUPERCONDUCTORS AND CONSEQUENCES FOR APPLICATIONS TO LINEAR DEVICES

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ABSTRACT

Experimental results for the surface impedance of the oxide superconductor $YBa_2Cu_3O_7$ in the frequency range from 3 to 90 GHz and the temperature range from 4.2 to 300 K are presented for single-crystalline and poly-cristalline layers. Today the best results were achieved with a film grown epitaxially on $SrTiO_3$ by pulsed laser ablation leading to a surface resistance of less than 8 mΩ at 86.7 GHz and 77 K. Therefore applications to microwave and millimeterwave components which require a much higher quality factor as realizable with normal conductors or which have to be miniaturized by some orders of magnitude can be envisaged. Furthermore "inductive films" with "electronically tunable" properties may be realized.

INTRODUCTION

The advantage of the new oxide superconductors (s.c.) is based on both the possibility of low-cost nitrogen cooling (77K) and an expected ionization frequency $f_{ion} \approx 8$ THz being much higher as with conventional superconductors like Nb or Nb_3Sn.

Considering potential applications one has to distinguish between components which take advantage of the unique (linear) properties of the surface impedance and other components where nonlinear effects (Josephsen devices etc.) are employed. This paper deals with the former class of devices.

After an introduction of the quantities which are used to describe the linear properties of the s.c., a number of experimental data are presented and discussed with respect to potential applications to passive microwave components.

REPRESENTATION OF THE PROPERTIES

Despite the fact that the mechanism of charge transport in the high-T_c superconductors is still unexplored, their electromagnetic properties may for temperatures $T < T_c$ be represented by the complex valued conductivity

$$\sigma(T) = \sigma'(T) - j\sigma''(T) \quad \text{with } \sigma''(T) = 1/\omega\mu_0\lambda^2(T) \qquad (1)$$

which is a function of frequency ω and where λ denotes the effective penetration depth. λ is found to be equal to the London penetration depth λ_L for s.c. with a small coherence length (1).

The surface impedance of a s.c. layer with thickness w much larger than λ_L is related to σ via

$$Z_s = \sqrt{\frac{j\omega\mu_0}{\sigma}} \, . \qquad (2)$$

It may be represented by a series- or parallel-connected equivalent circuit according to

$$Z_s = R_s + j\omega L_s = 1 / [1/R_p + 1/j\omega L_p]. \qquad (3)$$

The conductivity of a s.c. is characterized by a "large" inductive part and a much smaller but finite real part which represents dissipative losses. With $\sigma' \ll \sigma''$ one obtains from eqs. (1-3)

$$L_p \approx L_s \approx \mu_0\lambda_L(T), \; R_p = 2/(\sigma'(T)\lambda_L(T))$$

$$\text{and} \quad R_s \approx \omega^2 L_s^2/R_p = \omega^2 \sigma'(T)\mu_0^2\lambda_L^3(T)/2 \, . \qquad (4)$$

For the conventional superconductors the real part σ'(T) as well as $\lambda_L(T)$ are for frequencies far below the ionization frequency f_{ion} nearly frequency independent. The surface impedance is therefore well represented by an equivalent circuit composed of an inductance $L_p \approx L_s$ and a parallel-connected resistance R_p, both being frequency independent, too. Conversion to the series resistance leads according to eq.(4) to a ω^2-dependence of R_s in contrast to R_s^{nc} of a normal conductor (n.c.) where $R_s^{nc} \sim \omega^{0.5}$ holds. So, for practical purposes a performance parameter, the so-called "crossover frequency" $\omega_c < \omega_{ion}$ with $R_s^{nc} = R_s$ for a given temperature can be defined leading to

$$R_s/R_s^{nc} \approx (\omega/\omega_c)^{1.5} \, . \qquad (5)$$

Two points are important if applications of s.c. to linear components are envisaged: (α) Joule losses represented by R_s are for $f \ll f_c$ "much lower" than with normal conductors. (β) Surface inductance L_s of a s.c. is in contrast to the n.c. case nearly frequency independent.

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EXPERIMENTAL RESULTS

The surface impedance of the oxide superconductor $YBa_2Cu_3O_7$ was determined for polycrystalline bulk samples and thick film layers as well as for single-crystalline thin films. These results are obtained by placing the samples into cavities. Real and imaginary part of Z_s are determined from the change in quality factor and resonance frequency (2-4). All cavities are evacuated and some of them are for an increased sensitivity itself made from a conventional superconductor (Nb) and immersed into liquid helium (2-4). In Fig. 1 the pill-box copper cavity used for measurements in the millimeter-wave regime is shown. It can alternatively be operated in the TE_{013}-mode at 86.7 GHz where one endplate contributes 40 % to the losses or in the TE_{021}-mode with 5 % contribution.
The cavity was warmed up in a glass cryostat from 4.2 K to room temperature in about 8 h.

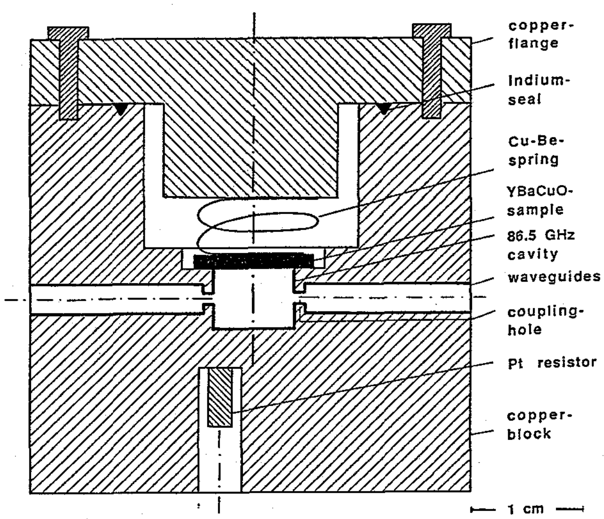

Fig. 1 : Cavity for measurements at 86.7 GHz

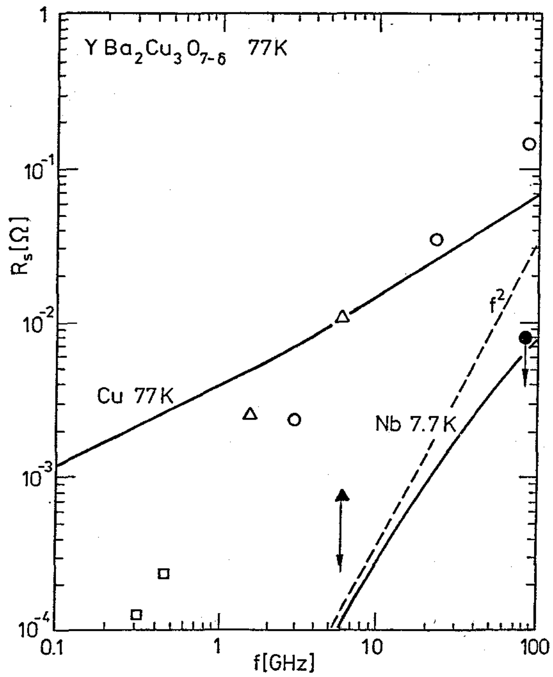

Fig.2: Frequency dependence of R_s at 77 K for polycrystalline (open symbols) and single-crystalline (full symbols) YBaCuO. Measurements at Argonne (squares, ref.6), Cornell (triangles, ref.5) and Wuppertal (circles).

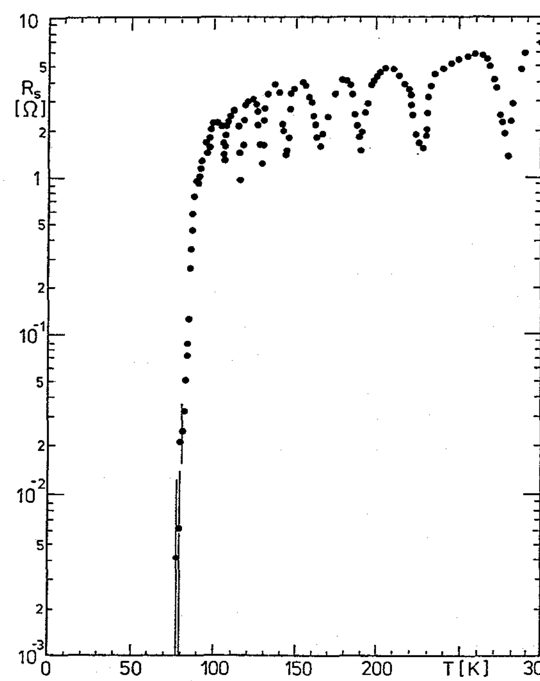

Fig.3:
Temperature dependence of the surface resistance of a single-crystalline layer at 86.7 GHz.

Fig. 2 gives an overview about results for R_s at 77 K found at Wuppertal, Cornell and Argonne (2-8). The open marks correspond to polycrystalline YBaCuO whereas results for single-crystalline layers are represented by full marks. For comparison the surface impedance of copper at 77 K and Niobium at 7.7 K is shown, too. Today the best results (full mark at 86.7 GHz in Fig. 2) were achieved with a c-axis oriented film grown epitaxially on $SrTiO_3$ by pulsed excimer laser ablation (7). Fig. 3 shows for this sample the temperature dependence of R_s at 86.7 GHz. A sharp drop is observed at $T_c \approx 87\,K$ with $R_s \approx 8\,m\Omega$ at 77 K. From this the crossover frequency f_c (see eq.(5)) can be estimated to be about 500 GHz. The

oscillations of R for $T \geq T_c$ result from interference with multiple reflections at the back walls of the substrate and the cavity. The London penetration depth at T=0 was deduced from these measurements to be in the order of $\lambda_L \approx 0.2$ μm (8). So, the parameters for the equivalent parallel connected circuit which are introduced in eq. (3) and are expected to be nearly frequency independent for $f \ll f_{ion}$ follow to be about $L_p \approx 0.25$ pH and $R_p \approx 2.3$ Ω.
The temperature dependence of R_s of the polycrystalline samples (bulk material and electrophoretically deposited layers (9)) turned out to be strongly influenced by the fabrication parameters (sintering time etc.,(3)). The lowest R_s-values for polycrystalline samples are about 50 times higher than the corresponding values for the single-crystalline layers, leading to a crossover frequency of about 20 GHz. This fact is considered to be due to intergrain resistivity and low conducting impurity phases.

APPLICATIONS

Utilization of low dissipation loss

A wide class of microwave components are designed to produce (theoretically) the desired function as non-dissipative multiport between resistive terminations, whereas the properties of real components are affected by unwanted dissipation loss. These losses may be represented by the unloaded quality factor $Q_0 = \omega W/P$, where W denotes the stored energy and P the dissipated power, which in general is the sum of Joule losses in the metallic layer and in the dielectric substrate.
In the case of open structures (e.g. microstrip circuits) additional radiation losses occur. To meet the required properties with respect to the frequency response, the efficiency or the effective noise temperature of the component, the unloaded quality factor has to exceed a minimum value Q_0^{min}. Relatively high values Q_0^{min} are required for those components which are characterized by a large group delay and therefore by a large amount of stored energy. Bandpass filters with extremely small bandwidth, pulse compression filters with high compression ratios, matching networks with very high transformation ratio and electrically small antennas are examples for this type of components (10).
A necessary condition for a useful application of superconducting instead of normalconducting wall material is that the n. c. Joule losses dominate the other loss contributions. In this case the value of Q_0 is crudely estimated by

$$Q_0 \approx 1.5 \frac{D}{\lambda} \frac{Z_0}{R_s} \quad , \qquad (6)$$

where D is a typical lineaı Dimension, λ the wavelength, $Z_0 = 377$ Ω and R_s the surface resistance. From this equation a "realizability plane" (Fig. 4) is deduced.

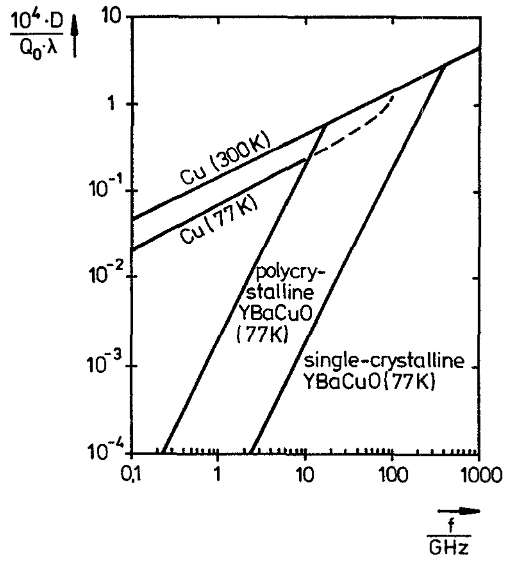

Fig.4: Realizibility of a component with given normalized unloaded quality factor Q_0 and frequency of operation. (Only losses within conductors are taken into account.)

Each point of this plane corresponds to a relative size of a component D/λ normalized to the value of Q_0 and its frequency of operation. The plane is divided into different regions by lines corresponding to copper at room temperature and to copper as well as polycristalline and single-crystalline YBaCuO at 77 K (liquid nitrogen). All f-(D/λ)-combinations belonging to a point above a line can be realized with the corresponding material.
From Fig. 4 one can deduce 3 different situations where superconductivity is of interest:
(α) In the millimeter- and submillimeter-wave regime moderate Q_0-values in the order of 10^2 to 10^4 can with normal conducting material only be achieved if highly overmoded structures (D»λ) are employed. This restriction may be overcome if superconducting layers are used and if furthermore additional loss-contributions as dielectric losses and radiation losses are kept sufficiently small. To cope with the dielectric losses in planar components the problem of s.c. film deposition onto low- tanδ-substrate has to be further investigated or one avoids this problem by using the "inverse strip line" (field mainly in vacuum and not in substrate).
(β) In the centimeter- and decimeter-wave regime moderate Q_0-values are easily obtained with normal conducting structures if the size D is in the order of the wavelength λ. In this case superconductivity offers the possibility of a miniaturization by some orders of magnitude (D/λ«1) using lumped instead of distributed elements. This allows the realization of much more complex circuits than with conventional techniques if space

restrictions have to be met (e.g. broadband matching and controlling network for radiating elements of a phased array antenna).

(γ) If extremely high Q_0-values ($Q \geq 10^6$) are required (e.g. for oscillator stabilization) one has to use superconducting material in any case.

As a consequence of the experimental results presented above at present applications belonging to case (α) and (γ) require single-crystalline layers whereas poly-crystalline layers (e.g. electrophoretically deposited layers) are today restricted to case (β).

Inductive films

A thin film (n.c. or s.c.) with thickness w less than the penetration depth and a complex conductivity σ is electromagnetically transparent and characterized by an impedance

$$Z_F = 1/\sigma w \quad . \tag{7}$$

This impedance describes the change in the tangential component H_t of the magnetic field strength across the film as a function of the tangential component E_t:

$$H_{t1} - H_{t2} = Z_F \, E_t \tag{8}$$

In contrast to a normal conductor where the impedance Z_F becomes resistive if the thickness is less than the penetration depth a superconductor leads to a nearly frequency independent inductance:

$$Z_f \approx Z_s \; \lambda_L(T)/w \; \approx j\omega\mu\lambda_L^2(T)/w \tag{9}$$

"Inductive films" may be utilized to build transmission lines with an "electronically tunable" phase constant (11,12). Fig. 5 shows a parallel-plate configuration (conducting layers 4 and 5 with dielectric substrate 2) where a "double layer" consisting of a s.c. inductive film (layer 1) and a thin isolator (layer 3) is inserted. If the thickness of the s.c. layer w is smaller than λ_L it results in a considerable reduction of the phase velocity. Furthermore, it can be shown that the "sensitivity" of the phase velocity to variations in λ_L is increased by a proper choice of the thickness d of the isolating layer 3. λ_L and therefore the wave velocity may be controlled by a d.c.-current which changes the Cooper pair density(11). Fig. 6 shows an application of the structure according to Fig. 5 to a microwave patch antenna. With the d.c. control current flowing through the s.c. film the phase constant in the patch region can be be varied resulting in a electronically tuned resonance (operating) frequency of the antenna.

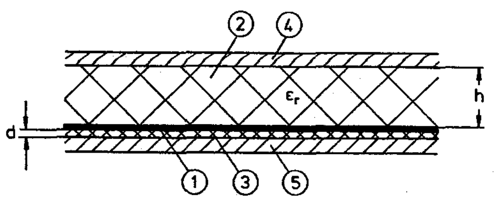

Fig.5: Parallel plate configuration with inductive film

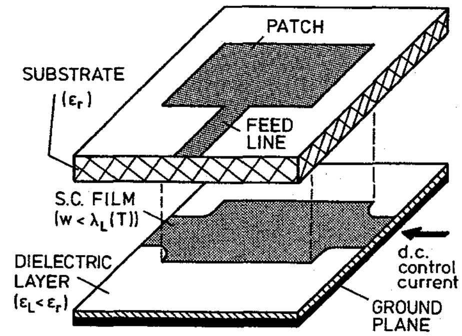

Fig.6: Electronically tunable microwave patch antenna

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