The intrinsic surface impedance of coated conductors

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Abstract. Coated conductors, i.e. superconducting thin films grown on tapes consisting in metallic substrates, is an enabling technology for the use of the high- $T_c$ YBa$_2$Cu$_3$O$_{7-\delta}$ superconductor in applications requiring long superconducting cables, such as high field magnets and electric power distribution grids. The largely used d.c. measurements of the material current carrying capabilities would benefit from being integrated and complemented by local measurements of the material complex a.c. resistivity. Despite the potential of this approach, high frequencies measurements are hindered by the highly conducting substrate, which obscures the superconductor response. In this manuscript we address the problem of extracting the superconductor impedance by properly taking into account the substrate contribution.

1. Introduction
Microwave measurements are a powerful and widespread tool for material characterization, allowing to measure surface impedances $Z$, dielectric permittivities and magnetic permeabilities [1]. Electromagnetic (e.m.) resonators, albeit limited to single (or few) operating frequencies, are widely used thanks to their high sensitivity. In the study and development of technologically viable superconductors, their sensitivity allowed to cope with the small values of the surface resistance of these materials, making resonator-based techniques a de facto standard [2]. One of the most promising modern superconductors is YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) [3]. This non-metallic material has poor mechanical properties which prevent the direct fabrication of long cables, needed for magnet coils and power transmission lines. The envisaged solution consists in the so-called coated conductor structure [4], in which YBCO thin films are grown on metallic tapes which provide the necessary mechanical support and flexibility. Besides d.c. measurements of the current carrying capabilities, surface impedance measurements can be exploited to study the coated conductor local complex resistivity, which qualifies as a complementary investigation tool [5, 6] for the zero-field and in-field properties. Indeed, this approach has been largely used for laboratory-grade films grown on insulating substrates. On the other hand, the microwave probing field partially penetrates the thin film leaking to the underlying metal which, therefore, contributes as an additional conductive layer. The resulting surface impedance arises as an admixture of both YBCO and metal resistivities. Our goal is to demonstrate the feasibility of this kind of measurements showing how the superconductor complex resistivity can be extracted.

2. Effective surface impedance in coated conductors
A typical YBCO coated conductor presents a multilayer structure, with buffer layers grown between the film and the metal substrate with the aim to improve the chemical and mechanical compatibilities. The sample under consideration here is depicted in the inset of Fig. 1b. It was
grown at ENEA [7] on an EVICO Ni-5at.%W alloy by Pulsed Laser Deposition and consists of a CeO2/YSZ/CeO2/Pd buffer multilayer, with thicknesses (15/110/45/200) nm, and a top flat YBCO film having thickness $t_s = 175 \pm 10$ nm. Other deposition details can be found in [8].

The physical quantity of interest is the surface impedance $Z$, which measures the response of the sample to an impinging microwave e.m. wave. For a “bulk” semi-infinite conducting material having complex resistivity $\rho$, in the local limit and normal skin effect [9], $Z = \sqrt{\omega \mu \rho}$, where $\omega = 2\pi f$ is the angular frequency, $f$ the frequency, $\mu_0$ the vacuum magnetic permeability. On a multilayer structure, the e.m. wave leaks through the top layer reaching the underlying layers. At each interface between layers partial reflection and transmission occur. The resulting effective surface impedance $Z'$ can be computed by repeated application of the following expression [9]:

$$Z'_{s} = Z_{s}Z'_{s} + iZ_{s}\tan(k_{s}t_{s}) = Z_{s}Z'_{int} + iZ_{s}\tan(k_{s}t_{s})$$

where the $i^{th}$ layer has effective surface impedance $Z'_i$, thickness $t_i$, characteristic impedance $Z'_c$ (equal to $\sqrt{\omega \mu_0 \rho}$ for conductors and to $\sqrt{\mu_0 / \varepsilon_0 \varepsilon_r}$ for lossless dielectrics with relative permittivity $\varepsilon_r$), wave propagation constant $k_i = \omega / \mu_0 \varepsilon_r$. By applying Eq. (1) to our sample, which comprises a superconductor thin film with complex resistivity $\rho_s$, grown over the buffered substrate having effective $Z'_{sub}$, its effective $Z'_c$ can be written as:

$$Z'_c = Z_{s}Z'_{sub} + iZ_{s}\tan(k_{s}t_{s}) = Z_{s}Z'_{int} + iZ_{s}\tan(k_{s}t_{s})$$

where we have introduced the so-called intrinsic impedance $Z_{int} = Z_{s}/(i \tan(k_{s}t_{s}))$ which contains quantities referring to the superconductor thin film only, and in particular its complex resistivity. Since $iZ_{s}\tan(k_{s}t_{s})$ is usually negligible for thin films with $t_s \ll \min(\lambda, \delta)$, where $\lambda$ and $\delta$ are the London and quasi-particle penetration depths, respectively, the last member of Eq. (2) makes explicit that $Z'_c \sim Z_{int} / Z'_{sub}$. In order to determine $Z_{int}$ through a measurement of $Z'_c$, it is therefore necessary to either know $Z'_{sub}$ or neglect it if possible. The latter approach is customarily followed in presence of insulating substrates, for which $|Z'_{sub}| \gg |Z_{int}|$ [10], as in microwave circuits. By contrast, thin films grown on metal substrates have $|Z_{int}| \sim |Z'_{sub}|$, so that $Z'_{sub}$ must be independently determined, in terms of both its real and imaginary parts.

We are now in position to address the main problem: the extraction of $Z_{int}(T)$ from the measured $Z'_c(T)$ when the substrate contribution $Z'_{sub}$ is not negligible. A variant of this problem was addressed in [11] for what concerns the magnetic field dependence at fixed $T$ of $Z_{int}$.

3. Determination of film intrinsic impedance

The sample $Z'_s(T)$, measured through the dielectric resonator technique [12], is reported in Fig. 1a. The error bars correspond to standard uncertainties evaluated as $u(R'_0)/R'_0 \sim 2\%$ and $u(\Delta X'_c) \approx 0.006 \ \Omega$ [13]. The needed $Z'_{sub}$ cannot be separately measured, since the thin film is grown in situ with the underlying layers. The approach here proposed takes advantage of the high resistivity of a superconductor in its normal state, i.e., above its critical temperature $T_c$. In this situation $Z_{int}$ is essentially real and quite large: a simple estimation can be done by taking typical values for the normal state resistivity of YBCO $\rho_n = 10^{-6}\ \Omega \cdot m$. Since the obtained $R_{int} \simeq 5.7 \ \Omega \gg R'_s(T_{ref} = 92 \ K > T_c) = (0.172 \pm 0.003) \ \Omega$ (see Fig. 1a), it is clear that the dominant contribution to $Z'_c$ above $T_c$ comes out from the conductive substrate. We can thus take the real part of Eq. (2) and use it to fit the experimentally measured $R'_c(T_{ref}) := R'_n$, being confident that the fit will be mainly sensitive to $Z'_{sub}$.

In order to proceed we use the nominal values for $Z_{int}(T_{ref})$ and a $Z'_{sub}$ numerically computed through Eq. (1) with e.m. properties of the various layers taken from literature, as follows. The
Ni-5at.%W alloy has a relative magnetic permeability $\mu_r = 1$ [14] and an almost $T$-independent $\rho_{N/W} = 25 \cdot 10^{-8} \, \Omega \cdot m$ [15, 16]. The Pd film approaches the bulk limit resistivity which we take as $\rho_{pd} = 5.0 \cdot 10^{-8} \, \Omega \cdot m$, a worst case value at our $T$ [17], chosen because of the expected low quality of the film directly grown over the textured Ni alloy. Finally, CeO$_2$ and YSZ have $\epsilon_r = 23$ and $\epsilon_r = 27$, respectively [18, 19]. The so computed $R'_n = 0.153 \, \Omega$ is near the measured value. From this starting point, we perform a fit of the experimental value by properly exploring the input parameter space. We found that the dielectric layers contribute with their overall thickness only, so that their $\epsilon_r$ are inessential. Also, the fit sensitivity to $\rho_{N/W}$ is low, requiring an unrealistic change of over 70% to fit $R_n'$. Finally, as expected, the sensitivity to $\rho_n$ and $t_s$ is very low: changing them by $\pm 80\%$ and $\pm 30\%$ (by far worst case estimations of their uncertainties), respectively, determines a change $< 0.5\%$ on the computed $R'_{n}$.

The fit is most sensitive on the Pd layer properties, which enter the computation through the ratio $\rho_{pd}/t_{pd}$ within a good approximation. We find that $\rho_{pd} = 6.55 \cdot 10^{-8} \, \Omega \cdot m$ yields the desired $R_n'$ (in passing, we note that by changing instead the nominal $t_{pd}$ we obtain essentially the same results). Since the analytical model is too cumbersome to make feasible the standard analytical propagation of uncertainties, we propagate the uncertainties numerically, exploiting the local linearity of the model. Considering the value $R'_n$ to be fitted with its uncertainty, we determine the range $[\rho_{pd,min}, \rho_{pd,max}]$ needed to cover the interval $[R'_n - u(R'_n), R'_n + u(R'_n)]$, taking then $u(\rho_{pd}) = (\rho_{pd,max} - \rho_{pd,min})/2 = 0.3 \cdot 10^{-8} \, \Omega \cdot m$ ($u(\rho_{pd})/\rho_{pd} \sim 5\%$).

Having determined $\rho_{pd}$, we can compute $Z'_{sub} = 0.170 + i0.175 \, \Omega$ and the experimentally unknown value $X'_s(T_{ref}) = 0.229 \, \Omega$, which will provide the reference value for the measured $\Delta X'_s(T)$. We then numerically propagate $u(\rho_{pd})$ to $u(Z'_{sub})$ and $u(X'_s(T_{ref}))$ as follows. For every dependency relationship $y = y(x_i)$, we take the input quantity $x_i = x_i \pm u_{x_i}$, we compute the output quantity $y = y(x_i)$ with $x_i \in [x_i - u_{x_i}, x_i + u_{x_i}]$, and then we use the resulting range $\Delta y$ for the estimation of $u(y) = \Delta y/2$. We find that the 2% relative uncertainty on $R'_n$ yields 2% and 1.5% relative uncertainties on $Z'_{sub}$ and $X'_s(T_{ref})$, respectively. Having determined $Z'_{sub}$ at $T_{ref} = 92 \, K$, we exploit the substantial $T$-independence of all the substrate layers e.m. properties and neglect the small temperature variations of $\rho_{pd}$, so that $Z'_{sub}$ is taken as constant vs $T$.

We can now invert Eq. (1) in terms of $Z_{int}$. By approximating $Z_s\tan(k_s t_s) \simeq \omega \mu_0 t_s$ [10], which involves a negligible error with respect to the other uncertainties, a straightforward expression in terms of experimental/fitted quantities only is obtained:

$$Z_{int} = \frac{Z'_{sub}Z'_s}{Z'_{sub} - Z'_s + i\omega \mu_0 t_s} = \frac{Z'_{sub}(R'_s(T) + i\Delta X'_s(T) + iX'_s(T_{ref}))}{Z'_{sub} - (R'_s(T) + i\Delta X'_s(T) + iX'_s(T_{ref})) + i\omega \mu_0 t_s}$$ (3)
The obtained $Z_{int}$ is reported in terms of its real $R_{int}$ and imaginary $X_{int}$ parts in Fig. 1b. It is worth noting that both $R'_s(T)$ and $X'_s(T)$ (the latter requiring, in turn, the knowledge of the reference value $X'_s(T_{ref})$) are required to determine separately $R_{int}$ and $X_{int}$. This is different from the situation with insulating substrates, where a single measure can provide $R'_s(T)$. The last member of Eq. (3) highlights the various quantities entering in the computation of $Z_{int}$, which is useful also to pinpoint the sources of uncertainty. First, there are the experimentally measured $Z_{s}(T)$ and $Z_{sub}(T)$, with uncertainties already discussed. Then, there are $X'_s(T_{ref})$ and $Z'_{sub}$, which are obtained together through the previously described fitting of the measured $R'_s$, and hence are correlated quantities whose uncertainties depend on the same $u(R'_s)$. Finally there are $t_s$ with its $u(t_s)$ and $\omega$, with negligible $u(\omega)/\omega \sim 1$ ppm. By taking all these uncertainties as independent (hence neglecting the correlation between $R'_s(T)$ and $X'_s(T)$), we first numerically propagate the contribution of each of them, separately to $u(R_{int})$ and $u(X_{int})$, following the procedure described before. We then combine them through the usual mean square root rule [20]. The so-obtained uncertainties are reported as error bars in Fig. 1b. It can be seen that near $T_c$ they increase dramatically, as a result of the inversion computed with Eq. (3) for small $T<T_c$. This is different with its $u(T)$ and $X'_s(T)$. The last

4. Conclusions

We have addressed the problem of extracting the intrinsic impedance of a superconducting thin film grown on metallic substrates. We have shown that the substrate needs to be separately characterized, and we have proposed a procedure which enables this characterization despite the unavailability of a bare substrate. We have shown that the obtained superconductor intrinsic impedance, yielding the material complex resistivity useful for deeper studies and/or material optimizations, is affected by uncertainties low enough to yield trustworthy figures.

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