RAPID COMMUNICATION

Radio frequency response of Ag-sheathed $(Bi, Pb)_2Sr_2Ca_2Cu_3O_{10+x}$ superconducting tapes

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Abstract. The response of long $(Bi, Pb)_2Sr_2Ca_2Cu_3O_{10}$ conductors fabricated by the oxide-powder-in-tube method to a radio frequency excitation was investigated while employed as the inductive part of large L–C resonating circuits. After removal of the outer silver sheath, superconducting devices cooled down to 77 K showed superior properties compared to equivalent non-superconducting circuits: Bi-based resonators, conceived for a working frequency in the range between 5 and 17 MHz, presented an improvement of the quality factor by a factor of 20. This result opens new perspectives for the application of Bi-based superconducting materials in the detection of a weak radio frequency signal, as in magnetic resonance imaging.

Over the years, the development of long Bi-based high-temperature superconducting (HTS) wires and tapes has been gradually focused towards their implementation in ac power transportation, transformation and storage. In the case of multi-core oxide-powder-in-tube (OPIT) processed silver-sheathed $(Bi, Pb)_2Sr_2Ca_2Cu_3O_{10}$ (Bi(2223)/Ag) tapes [1], silver alloying [2, 3], filament twisting [4], resistive oxide barriers [5, 6] and innovative tape configurations [7–9] have been in turn introduced in order to reduce the relevant ac losses appearing when they are subjected to an alternating current flow. With these modifications, Bi(2223)/Ag superconducting tapes are increasingly approaching the technological requirements of power industries for their introduction into the electrical power grid. Still in the field of large-scale applications of HTS materials, promising results have recently been achieved by the introduction of the so-called IBAD [10, 11] and RABITs [12] methods, which are scalable processes for the fabrication of thin, epitaxially grown $Y_1Ba_2Cu_3O_{7-\delta}$ (YBCO) layers on metallic, strong and flexible substrates.

Much less is known about the response of these functional conductors over a much wider frequency domain, in which other practical applications on a smaller scale can take advantage of their unique properties. The high-frequency domain covering the radio frequencies (RF) has been historically dedicated to thin-film technology, which has been considered so far more suitable for these special applications. HTS films are indeed known to present a much smaller surface resistance in the microwave region than any normal conductor at room temperature [13]. In particular, strong efforts have been focused on the development of thin-film-based, highly efficient passive microwave devices as antennas and filters [14]. One of their first commercial applications will probably be the band-pass filter for base stations of wireless communications.

The need to cover large, intricate surfaces with high-quality, epitaxially grown HTS films, as required by a number of RF applications, is still a problem that has to be overcome in an economic way for these materials [15]. Pick-up coils for both total body and dedicated magnetic resonance imaging (MRI) commercial systems are amongst those applications that can benefit from an extended superconducting path, and have already been studied in the form of planar coils based on YBCO thick and thin films. In this case, an improved signal-to-noise ratio (SNR) compared to those of otherwise identical copper and silver resonators has already been reported [16, 17].

Three-dimensional detectors are, however, more appropriate to collect the signal generated by extended samples, as the portions of the human body analysed with an MRI scan typically are. We have therefore developed Bi(2223)-based conductors that can be successfully used to assemble arbitrarily large as well as intricate detectors for high-frequency signals, leading to highly improved SNR values. We report about the preparation route as well as the typical properties we have achieved with L–C circuits

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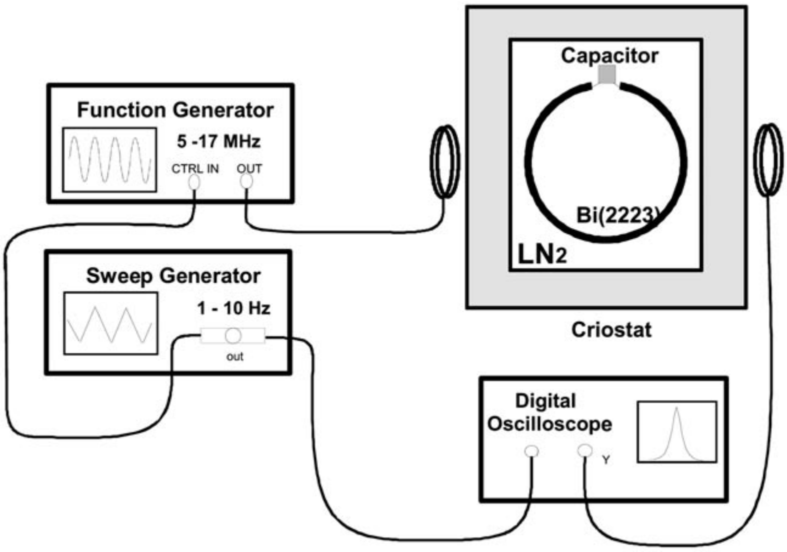

Figure 1. Scheme of the experimental set-up for the determination of the quality factor.

resonating at frequencies between 5 and 17 MHz, which is a domain of interest for dedicated MRI detectors.

The typical conductor we have employed for the assembly of the RF L–C resonators is a modified Ag-sheathed Bi(2223) tape fabricated by the OPIT method [1], characterized by a thickness of 250 μm, a width of 3 mm and a 77 K critical current of about 35 A. Tapes have been prepared with different configurations of the superconducting core, which have been progressively adapted to the high-frequency application. Wire-in-tube [18] as well as 19-filament conductors [19] have been preferred with regard to a simpler conductor geometry for mechanical strength advantages. It has to be taken into account, indeed, that all the common OPIT conductors present an outer metallic shell that has to be completely removed in order to avoid the complete screening of the superconducting phase from the RF signal. In fact, pure silver and silver-based alloys (chemically compatible with the Bi(2223) phase) present 77 K electrical resistivity values that lead to a skin depth penetration of the RF excitation (2–20 MHz) of the order of 10–30 μm, i.e. shorter than the usual outer sheath thickness.

The removal of the outer silver sheath is carried out by dissolving it completely with a proper etching solution based on ammonium hydroxide (50 vol% aqueous solution) and hydrogen peroxide (30 wt% aqueous solution), mixed in equal amounts and partly diluted by distilled water (by about 50 vol%) [20]. The conductor is wound around an adequate cylindrical PVC support that protects and keeps it in a fixed position during the etching as well as during the testing process in the liquid nitrogen bath. The effectiveness of the etching solution was tested both by optical and x-ray diffraction analysis. No apparent degradation of the Bi(2223) phase microstructure at the end of the etching process has been observed in the x-ray diffraction pattern, and an analogous response was obtained from the scanning electron microscopy and the atomic force microscopy investigation of the Bi(2223) filamentary surface.

L–C resonators are assembled by directly soldering a capacitance C between 150 to 1000 pF at the ends of the Bi(2223) conductor wound in circular turns. Very high-quality multilayer capacitors are chosen for this purpose, mostly those manufactured by Dielectric Labs Inc. (USA) and by American Technical Ceramics (USA). The resonating circuits are characterized by a resonance frequency f_0 and by a quality factor Q which are respectively given by

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

and

$$Q = 2\pi f_0 \frac{L}{R} \tag{2}$$

where L is the inductance of the superconducting pick-up coil and R is the overall resistance of the circuit, which is given by the sum of the series resistance of the pick-up coil and of the capacitance itself. A real capacitance can indeed be roughly schematized by an equivalent circuit composed by an ideal capacitor of identical value with a parallel resistance R_c, that determines its quality factor Q_c, which is given by $2\pi f_0 R_c C$. Ideally, Q_c should be much larger than Q, in order to limit the influence of the capacitor on the measurement. While no precise information from the manufacturers about Q_c at 77 K has been acquired, it is expected that it exceeds 10^4 in the frequency and temperature domains we have investigated. Typical L values we have achieved are comprised within the range 0.3–1.8 μH, and are constituted by one to three turns of an etched Bi(2223) conductor wound in spirals of about 11 cm in diameter.

The experimental technique we have employed to measure the quality factor Q is schematically represented in figure 1. In this set-up, the L–C resonator is directly immersed in liquid nitrogen. This experimental set-up has been chosen because it presents a very weak coupling between the L–C resonator and the excitation and detection coils. The excitation signal is generated by a small coil which is supplied by a signal generator with sweeping frequency centred around f_0. A digital oscilloscope collects the signal detected by a small pick-up coil and represents it as a function

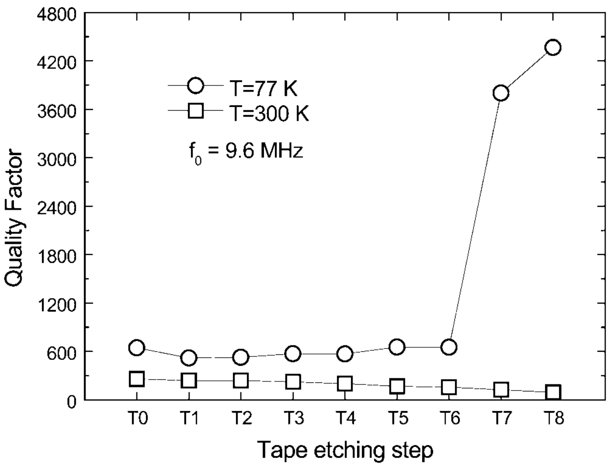

Figure 2. Quality factor of a single turn Bi(2223)-based L–C resonator at different stages of the etching process of the outer silver sheath (T0–T8).

Table 1. Summary of the results achieved on the Bi(2223) L–C resonators at 77 K. All the resonators have been assembled with a 19-filament conductor except for the last one.

Inductance specifications (turns, diameter, tape length)	C (pF)	f_0 (MHz)	L (μH)	Q
1 turn, $\oslash = 11$ cm, $l = 36$ cm	940	9.61	0.29	4400
1 turn, $\oslash = 11$ cm, $l = 36$ cm	470	13.3	0.3	3800
1 turn, $\oslash = 14$ cm, $l = 44$ cm	235	16.8	0.38	3400
2 turns, $\oslash = 11$ cm, $l = 74$ cm	940	5.4	0.92	6500
2 turns, $\oslash = 11$ cm, $l = 74$ cm	470	7.65	0.92	6700
2 turns, $\oslash = 11$ cm, $l = 74$ cm	313	9.42	0.92	5600
2 turns, $\oslash = 11$ cm, $l = 74$ cm	156	13.1	0.94	4700
3 turns, $\oslash = 11$ cm, $l = 110$ cm	470	5.55	1.75	7200
3 turns, $\oslash = 11$ cm, $l = 110$ cm	235	7.86	1.74	7900
1 turn, $\oslash = 11$ cm, $l = 36$ cm wire-in-tube tape	940	9.6	0.3	3500

of the sweep generator signal. The experimental quality factor value is given by $Q = f_0/\Delta f$, where Δf is the frequency width of the power resonance curve measured at a level of -3 dB.

The quality factor Q of a single turn L–C resonator has been initially evaluated at several intermediate stages of the chemical etching procedure. The measurements have been carried out both at room temperature and in liquid nitrogen, and are presented in figure 2 as a function of the number of etching steps, which are separated by 15 s of immersion in the etching bath. In this way, the resonance frequency is about 9.6 MHz, while the inductance is approximately 0.3 μH. A sharp increase in the quality factor at 77 K has been observed when the outer silver sheath is almost completely dissolved. More accurately, the superconducting resonator presents an improvement of the quality factor by about 20 if compared to the result achieved on a similar resonator measured at room temperature and presenting an intact silver sheath.

Considering that the SNR of such an antenna is proportional to $Q^{1/2}$, the present result should translate into an improvement of the SNR by a factor larger than four.

Many L–C resonators have been afterwards assembled, the main results being summarized in table 1. For these coils the etching process has been carried out in a single step. We have observed that the quality factor steadily increases with the number of turns of the resonators, implying that the homogeneity along the length of the Bi(2223) conductors is largely adequate at these frequencies. On the other hand, a smooth maximum in the frequency dependence of the quality factor is also observed, as a result of a predictable increase in the resistance of the superconductor as a function of the frequency that has to be taken into account in equation (2). At present, the highest quality factor of 7900 has been achieved by the three-turn resonator at a frequency of 7.86 MHz. The result in terms of quality factor is about a factor of two larger than that for a planar YBCO thick film device of comparable size and already proven efficiency [16]. Moreover, considering the fact that the L–C resonator of commercially available, dedicated MRI systems typically presents a Q factor below 1000 at a frequency of about 8 MHz, with an inductance composed by a multiple turn (>3) coil of comparable size to the Bi(2223)-based ones, it is expected that a large improvement in the MRI image quality and/or in the reduction of the acquisition time can be achieved in the near future with superconducting resonators. This promising result is also a consequence of the fact that, once the silver sheath has been removed, the exposed Bi(2223) layers present the best transport properties, grain alignment and phase purity with regard to the overall properties of the superconducting core [21–23]. It is expected that the results will be further improved by the introduction of new filament and tape configurations that can better match the requirements of RF detectors.

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