Microwave Response of Coaxial Cavities Made of Bulk Magnesium Diboride

Aurelio Agliolo Gallitto, Pietro Camarda, Maria Li Vigni, Alessandro Figini Albisetti, Luca Saglietti, and Giovanni Giunchi

***Abstract*—We report on the microwave properties of coaxial cavities built by using bulk MgB_2 superconductor prepared by reactive liquid Mg infiltration technology. We have assembled a homogeneous cavity by using an outer MgB_2 cylinder and an inner MgB_2 rod and a hybrid cavity by using an outer copper cylinder and the same MgB_2 rod as inner conductor. By the analysis of the resonance curves, in the different resonant modes, we have determined the microwave surface resistance R_s of the MgB_2 materials as a function of the temperature and the frequency, in the absence of dc magnetic fields. At $T = 4.2$ K and $f \approx 2.5$ GHz, by an mw pulsed technique, we have determined the quality factor of the homogeneous cavity as a function of the input power up to a maximum level of about 40 dBm (corresponding to a maximum peak magnetic field of about 100 Oe). Contrary to what occurs in many films, R_s of the MgB_2 material used does not exhibit visible variations up to an input power level of about 10 dBm and varies less than a factor of 2 on further increasing the input power of 30 dB.**

***Index Terms*—Cavity resonators, superconducting microwave (mw) devices, surface impedance.**

I. Introduction

MICROWAVE (mw) devices, such as filters, antennas, and resonators, can be conveniently assembled by superconducting materials, which have microwave surface impedance lower than normal conductors [1]–[3]; in particular, superconducting resonators are of great interest for both applicative and fundamental aspects. Different prototypes of superconductor-based resonators have been built, and a renewed interest of the research on this field occurred after the discovery of high-T_c cuprate superconductors (HTSs) [1]–[3]. In the last years, attention has been mainly devoted to planar-transmission-line filters or strip-line resonators and, consequently, to the characterization of superconducting films by which small-size devices can be developed. However, bulk-cavity filters provide higher quality factor and reduced nonlinear effects; hence, they can be conveniently used in all the applications in which miniaturization is not important [4].

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Since the discovery of MgB_2 superconductor with $T_c \approx$ 39 K, several authors have indicated this material as promising for mw applications [5]–[7], looking particularly at the realization of mw cavities for particle accelerators. Still now, several groups investigate the properties of MgB_2 with the aim to demonstrate its suitability for mw applications, particularly in films [8]–[10]. The advantage in using MgB_2 rather than conventional superconductors is its higher T_c, which can be easily reached by little expensive closed-cycle cryocoolers. On the other hand, although the transition temperature of MgB_2 is noticeably smaller than those of HTS, the reduced effects of the granularity in MgB_2 allow one to overcome the main problems limiting the use of HTS. Indeed, it has been shown that, contrary to oxide HTS, in MgB_2 only a small amount of grain boundaries act as weak links [11]–[13], reducing the field dependence of its critical current and nonlinear effects.

Soon after the discovery of superconductivity in MgB_2, researchers at Edison SpA (Milan, Italy) have developed the reactive liquid Mg infiltration technique (Mg-RLI) [14] to produce bulk MgB_2 samples. It has been shown that this technique is particularly suitable to obtain high-density bulk MgB_2 materials, showing very high mechanical strength and high machinability [15]. Moreover, bulk MgB_2 of different shapes, particularly long wires and hollow cylinders, can be built by Mg-RLI technique [16]–[18]. To our knowledge, the only two mw devices up to now produced have been built using MgB_2 prepared by this technique [19], [20]. The first prototype was a cylindrical cavity exhibiting a quality factor on the order of 10^5 in a wide range of temperature [19]; the second is a reentrant cavity for the experimental detection of the dynamic Casimir effect [20].

MgB_2 produced by the Mg-RLI technique can be exploited to manufacture mw coaxial resonators; on the other hand, up to now, MgB_2 coaxial resonators have never been tested. Prototypes of coaxial resonators have been built using normal metal as the outer conductor and HTS as the inner conductor [21]–[23]. Although this type of resonator was initially proposed to conveniently measure the frequency dependence of the mw surface resistance of the inner superconductors [1], it has been shown that it is particularly suitable to characterize samples of large dimensions in both linear and nonlinear regimes [23]. Further applications of coaxial cavities can be found in particle accelerators to couple the external power source to the accelerating cavity system [24], [25], as well as in all the filtering systems in which substitution of waveguides with coaxial lines allows one to achieve reduced dimensions.

In this paper, we discuss the mw properties of cylindrical coaxial cavities built by using bulk MgB_2 superconductor produced by the Mg-RLI technique. In particular, we have assembled a hybrid cavity, with the external cylinder of copper and internal rod of MgB_2, and a homogeneous cavity, with both external cylinder and internal rod of MgB_2. The mw properties of the homogeneous MgB_2/MgB_2 cavity have been checked closing the external cylinder with two different pairs of lids, i.e., one made of brass and another made of MgB_2. The aim of this paper was to perform a feasibility study in using MgB_2 for manufacturing coaxial cavities and to characterize the MgB_2 material.

II. Reactive Liquid Mg Infiltration Technology and Cavity Design

The reactive liquid Mg infiltration technology consists in the reaction, under thermal treatment, of pure liquid Mg and a preform of B powder in a sealed stainless-steel container [14], [15]. By this technique, it is possible to obtain high-density ($\approx$2.4 g/cm^3) bulk MgB_2 objects of large dimensions, whose shape can be varied properly designing the stainless-steel container. Moreover, samples prepared by Mg-RLI do not need to be kept in protected atmosphere to avoid degradation. The quality of the material depends on the purity and the grain size of the B powder [18], [26]. The final products consist in well-connected grains [18], [26] having the same dimensions as the starting B powder embedded in a finer grained matrix containing mainly MgB_2 with a few percent of Mg; only for material produced using B powder of grain size up to 100 μm, some amount of Mg_2B_{25} phase is present into the grains [27]. Several studies have indicated that better properties, such as higher critical current density, grain connectivity, reduced electromagnetic (EM) energy losses, and nonlinearity, can be reached by using fine B powder of about 1 μm in size [13], [26], [28]. However, because of the shorter percolation length of the liquid Mg into very fine B powder, the production of massive MgB_2 samples by Mg-RLI using micrometric B powder turns out to be more elaborated [18]; hence, an accurate choice of the B powder has to be done to obtain homogeneous thick specimens.

All the MgB_2 materials of the cavities discussed here have been prepared using crystalline B powder, with 99.5% purity, obtained by mechanically crushing the original chunks and sieving it under a 38-μm sieve. The temperature dependence of the dc resistivity of the MgB_2 material is shown in Fig. 1. From the curve of $\rho(T)$, it is possible to determine two parameters, i.e., the residual resistivity ratio (RRR) $\equiv \rho(300\ \mathrm{K})/\rho(T_c)$ and the effective current-carrying cross-sectional area of the sample $A_F = \Delta\rho_g/[\rho(300\ \mathrm{K}) - \rho(T_c)]$, where $\Delta\rho_g$ is the variation of the normal-state resistivity of ideal grains from 300 K to T_c. A_F gives indications on the grain connectivity, but its value depends on that taken on for $\Delta\rho_g$. Rowell [29] assumed that $\Delta\rho_g = 4.3\ \mu\Omega\cdot\mathrm{cm}$, considering the in-plane resistivity of a single crystal, whereas Jiang *et al.* [30] used $\Delta\rho_g = 7.3\ \mu\Omega\cdot\mathrm{cm}$, considering the resistivity of high-density wires produced by chemical vapor deposition. Yamamoto *et al.* [31] have calculated the expected $\Delta\rho_g$ considering a 3-D site percolative model that takes into account also the anisotropy of grains in polycrystalline samples; they show that the results obtained in a series of bulk samples are quite well accounted for using $\Delta\rho_g = 6.32\ \mu\Omega\cdot\mathrm{cm}$.

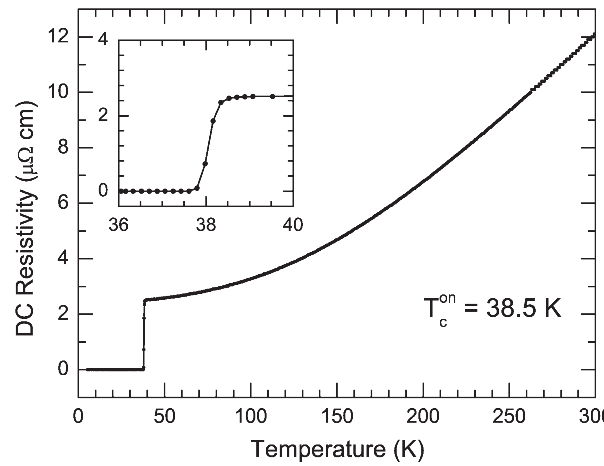

Fig. 1. Temperature dependence of the resistivity of the MgB_2 material used to compose the cavities here investigated. (Inset) Zoom of the curve around the transition temperature.

From the data in Fig. 1, we obtain RRR ≈ 4.9, and using the value of $\Delta\rho_g$ suggested by Yamamoto *et al.*, we obtain $A_F \approx 0.66$. These results, as compared with those deducible from the data reported in the review paper of Rowell [29], as well as with the more recent data for bulk samples [31], [32], show that our material exhibits good grain connectivity. In particular, $A_F = 0.66$ is very high with respect to those reported in the literature for polycrystalline samples; this can be ascribed to the fact that grain boundaries in MgB_2 produced by Mg-RLI are predominantly constituted by metallic Mg. The value of the critical current density, at $T = 4.2$ K in the absence of magnetic field, is $J_{c0} \approx 5\times10^5\ \mathrm{A/cm^2}$ and shows relatively weak dependence on the magnetic field [26] with respect to that observed in films [8], [9].

We have prepared two different coaxial cavities using bulk MgB_2. A homogeneous cavity is composed by an outer MgB_2 cylinder and an inner MgB_2 rod, and a hybrid cavity is composed by an outer copper cylinder and the same MgB_2 rod. The hybrid cavity has been used to understand if the inner rod and the external cylinder exhibit the same mw surface resistance. The mw properties of the homogeneous MgB_2/MgB_2 cavity have been checked closing the external cylinder with two different pairs of lids, i.e., one made of brass and another made of MgB_2. These different assemblies allowed us to check the feasibility to combine MgB_2 with other materials and to quantify the energy losses occurring in the cavity ends.

To produce the outer MgB_2 cylinder and the inner MgB_2 rod, different placements of Mg and B inside the steel container have been used. The MgB_2 hollow cylinder has been prepared by filling a steel tube with B powder and a central Mg rod. Crystalline B powder of average sizes less than 38 μm (P38 grade of STARCK AG(D), 99.5% purity) has been used, and a thermal treatment at 850 °C for 3 h has been done. After the reaction, the steel container and internal residual Mg have been removed by machining operations. The resulting MgB_2 tube has the following dimensions: 60-mm length, 12.8-mm inner diameter, and 20-mm outer diameter.

Fig. 2. (Top) A prospective view of the MgB_2 cylinder, which is a part of the homogeneous coaxial cavity; in the image, one can see the two brass rings, successfully soldered by using tin as soldering paste on a thin layer of copper electrodeposited on the outer surface of the MgB_2 cylinder; (bottom left) one of the brass adapters; (bottom right) one of the adapters made using a MgB_2 disk.

To prepare the inner MgB_2 rod, a steel tube with an internal diameter of 4 mm has been filled by the same crystalline B powder of average sizes less than 38 μm and the powder has been pressed reaching a packing density of almost 1.4 g/cm^3. At both ends of the container, two cylinders of magnesium have been put in contact with the boron powder and the whole system has been subjected to a thermal treatment at 850 °C for 3 h. The resulting MgB_2 rod has a diameter of 3.8 mm and a length of 45 mm. The MgB_2 lids have been obtained by cutting them by electroerosion from a thicker cylinder, with a diameter of about 35 mm, prepared with the same disposition of B and Mg as the inner rod; the disks are about 2 mm thick.

In order to investigate the mw properties of the coaxial cavities, it is necessary to couple the cavity with the RF excitation and detection lines using two adapters for the connection to the external lines. For the homogeneous cavity, we have tested two different pairs of adapters, i.e., one using brass disks and another using MgB_2 disks. Each adapter consists of a brass (or MgB_2) disk, having a central hole, at which it is fixed a coaxial cable ending with an SMA connector. The central conductor of the coaxial cable acts as an antenna. To couple the hybrid cavity with the external lines, we have used the brass adapters.

Fig. 2 shows the MgB_2 cylinder used for assembling the homogeneous cavity (top). The ends of the external cylinder are soldered to two brass rings on which the adapters have been attached. In order to solder the rings on the MgB_2 tube, the outer surface of the MgB_2 cylinder has been carefully polished obtaining a perfectly smoothed surface, on which it was possible to perform an electrodeposition of a thin layer of copper. The soldering operation was successfully done using tin as soldering paste. The bottom plot in Fig. 2 shows one of the two brass adapters and one of the adapters assembled using a MgB_2 disk.

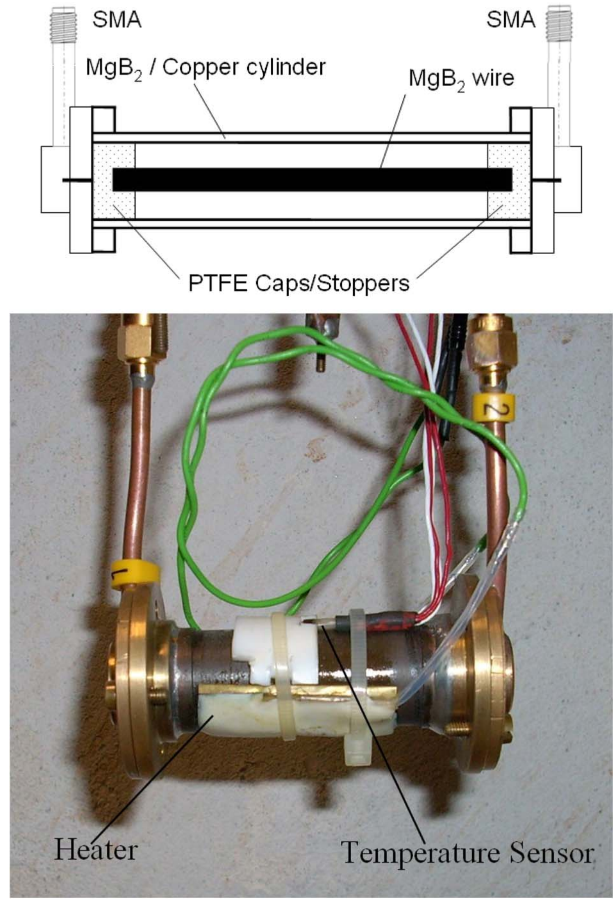

Fig. 3. (Top) Schematic of the coaxial cavity. (Bottom) Photo of the MgB_2/MgB_2 cavity assembled with brass adapters.

To coaxially assemble the inner and outer conductors, the inner rod is inserted into two PTFE stoppers, having a blind hole, that match with the external tube. Each stopper, which covers the inner rod for about 2 mm and extends up to the end of the external tube, forms a gap between the antenna and the end of the inner rod, preventing intermittent electrical contact.

A schematic of the coaxial cavity is reported in Fig. 3 (top), whereas a photo of the homogeneous MgB_2/MgB_2 coaxial cavity, with brass adapters, is shown in the bottom plot in Fig. 3. The characteristic impedance of the cavities is $Z_0 \sim 70\ \Omega$.

III. Experimental Apparatus and Analysis Methods

In order to investigate the mw properties of the coaxial cavities, we have used two different methods for the measurements at low power ($P_{\mathrm{in}} \lesssim 0$ dBm) and for the measurements as a function of the input power. At low power levels, the loaded quality factor of the cavities Q_L has been measured using an HP8719D network analyzer (NA), operating in the frequency range of 50 MHz–13.5 GHz and detecting the frequency response of the transmitted signal (S_{12}). The design of our cavities is such that only TEM modes can be fed, corresponding to stationary waves in which an integer number of half wavelength nearly matches with the length of the inner conductor. In TEM modes, electric-field lines are radial and magnetic-field lines wind around the inner rod; the positions of zeros and/or maxima of magnetic and/or electrical fields depend on the resonant mode, but in all TEM modes, at both ends of the inner conductor, the electric field is maximum and the magnetic field is zero. The NA generates continuous waves (cw) with a maximum intensity value of 5 dBm; sweeping the frequency of the cw in opportune ranges, we have detected the resonance curve of the cavity in the different TEM modes. By Lorentzian fits, we have found the central frequency and the half-height width of the resonance curves, from which we have determined Q_L.

The measured quality factor Q_L includes the energy losses at the walls of the outer and inner conductors, by which the cavity is made, as well as additional losses out of the ports coupling the cavity with the excitation and detection lines. To determine the mw surface resistance of the superconducting material, it is necessary to obtain the intrinsic quality factor Q_U, which is related only to the energy losses occurring at the cavity walls. To this end, we have measured directly by the NA the reflected signal at port 1 (S_{11}) and that at port 2 (S_{22}); by S_{11} and S_{22}, we have determined the coupling coefficients, i.e., β_1 and β_2, for both the coupling lines, as described in [1]. Thus, Q_U is calculated as

$$Q_U = Q_L(1 + \beta_1 + \beta_2). \tag{1}$$

From Q_U, one can determine R_s (see [1, Chap. III]). In particular, for the hybrid MgB_2/Cu cavity

$$R_s = \frac{1}{Q_u}\left[a\mu_0\omega \ln\left(\frac{b}{a}\right)\right] - \frac{a}{b}R_s^{\mathrm{Cu}} \tag{2}$$

where a is the radius of the MgB_2 rod, b is the inner radius of the outer Cu conductor, R_s^{Cu} is the surface resistance of the Cu tube, and ω is the angular frequency of the considered mode.

For the homogeneous MgB_2/MgB_2 cavity, (2) reduces to

$$R_s = \frac{1}{Q_u}\left[\frac{\mu_0\omega \ln(b/a)}{1/a + 1/b}\right]. \tag{3}$$

It is worth noting that, in principle, one would consider the dielectric loss due to the PTFE cups, which should be subtracted to $1/Q_U$ before calculating R_s; we have neglected this contribution because it is at least one order of magnitude smaller than $1/Q$. This point will be discussed after we report the results obtained for $Q(T)$.

The analysis of the resonance curves in the different TEM modes and (1)–(3) allowed us to determine R_s of the MgB_2 material used to build the cavities at different frequencies; the measurements have been performed in the range of temperatures 4.2–77 K. A cryostat and a temperature controller allowed us to work either at fixed temperatures or at temperature varying with a constant rate.

We would like to remark that (2) and (3) do not account for the small energy losses at the surface of the adapters due to the capacitive coupling. Since these additional losses cannot be calculated, an error in the determination of R_s will come into play, which increases on increasing the surface resistance of the material by which the adapters are made; for this reason, we have tested two types of adapters.

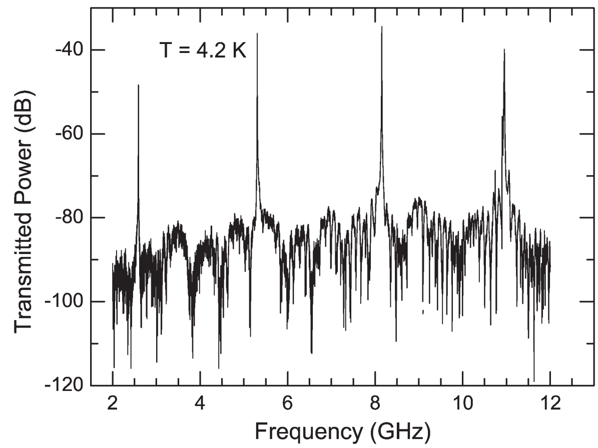

Fig. 4. Spectrum of the homogeneous coaxial cavity with MgB_2 cylinder, MgB_2 rod, and brass lids.

Measurements of the quality factor at different power levels have been done only with the homogeneous MgB_2/MgB_2 cavity, closed with MgB_2 lids, at the fundamental mode ($f = \omega/2\pi \approx 2.6$ GHz). In this case, the cw generated by the NA is modulated to obtain a train of mw pulses, with pulsewidth $\approx 10\ \mu$s and pulse repetition rate of 10 Hz. The pulsed signal is amplified up to a peak power level of ≈ 44 dBm and driven into the cavity through the excitation line. The transmitted pulsed power is detected by a superheterodyne receiver [33], which is equipped by a 30-MHz logarithmic amplifier that provides an output voltage proportional to the transmitted power. The signal is displayed by a digital oscilloscope and automatically acquired by an IEEE-488 interface. By acquiring the trace of the oscilloscope, we have measured the decay time τ of the transmitted power and determined the loaded quality factor as $Q_L = \omega\tau$. In order to determine Q_L by this method, it is necessary that τ is longer enough than the time response of the mixer of the superheterodyne receiver; for such reason, we have done these measurements using the cavity that exhibits the highest quality factor. Moreover, to avoid EM heating, the measurements as a function of the input power have been performed at $T = 4.2$ K, with the cavity in the liquid-He bath. Since the mw amplifier works only in the frequency range 2–4 GHz, these measurements have been done only at the fundamental resonant mode.

IV. Experimental Results and Discussion

A. Results at Low Input Power

Measurements as a function of the temperature and/or the frequency have been performed at low input power levels ($\lesssim 0$ dBm). The coupling coefficients at low temperatures are ~ 0.2 for both the ports and decrease with increasing the temperature; this implies that the values of R_s at the different temperatures refer to different effective input power inside the cavity. However, since no variations of the cavity properties have been found for $P_{\mathrm{in}} \lesssim 10$ dBm (as we will see in the following section), the $R_s(T)$ curves cannot be affected in any way by the temperature variation of the coupling coefficients.

Fig. 4 shows the spectrum of the homogeneous MgB_2/MgB_2 cavity closed with brass lids obtained at $T = 4.2$ K; it shows

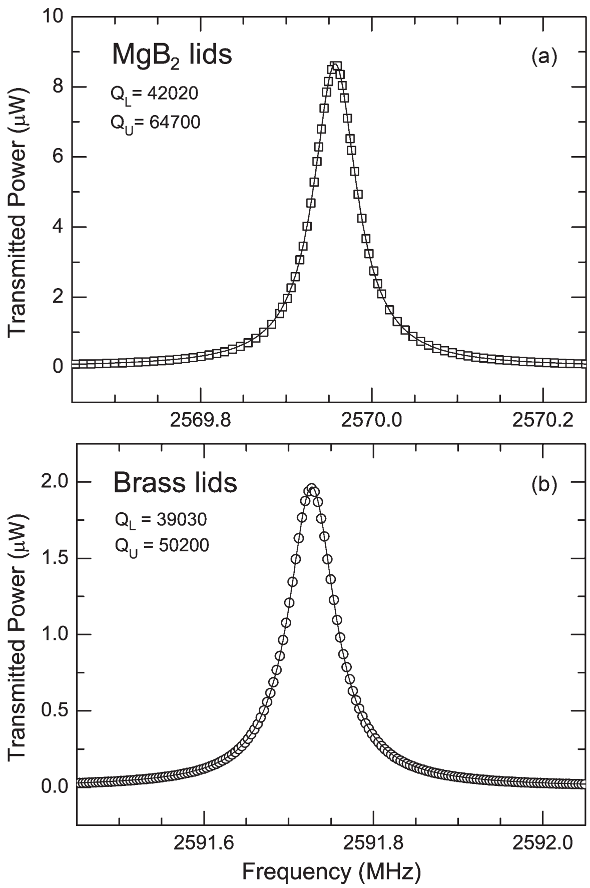

Fig. 5. Resonance curve at $T = 4.2$ K obtained at the fundamental TEM mode in the homogeneous MgB_2/MgB_2 coaxial cavity closed with (a) MgB_2 lids and (b) brass lids. The lines are Lorentzian fits of the experimental data.

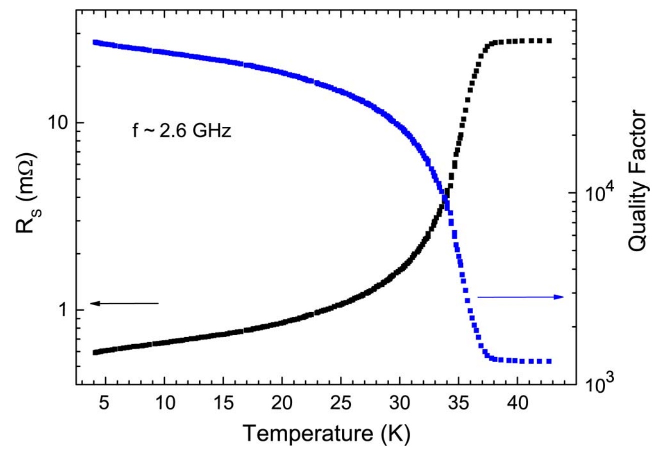

Fig. 6. Temperature dependence of (right axis) the unloaded quality factor and (left axis) mw surface resistance obtained in the homogeneous MgB_2/MgB_2 coaxial cavity, with MgB_2 lids, at the frequency of the fundamental TEM mode.

four resonance curves centered approximatively at 2.6, 5.3, 8.2, and 11 GHz. The resonant frequencies of the different modes do not match with the expected ones because the EM field extends slightly beyond the ends of the inner superconductor due to the capacitive effects at the gaps between the inner rod and the adapter. Similar spectra have been obtained in the homogeneous cavity closed with MgB_2 lids and in the hybrid MgB_2/Cu cavity. The only significant difference is the wider bandwidth of the resonance curves of the hybrid cavity due to the higher energy losses in the copper-cylinder walls.

Fig. 5 shows the resonance curves of the homogeneous coaxial cavity for both brass and MgB_2 lids, obtained at $T = 4.2$ K at the fundamental TEM mode. The lines represent the best fit curves of the experimental data, obtained by Lorentzian fits, which allow us to determine the loaded quality factor and the resonance frequency. From Q_L and (1), using the previously measured values of β_1 and β_2, we determined the unloaded quality factor. For this mode, we obtained the highest unloaded quality factor; in particular, for the homogeneous cavity closed by MgB_2 lids, $Q_U \approx 65\,000$, and for that closed by brass lids, $Q_U \approx 50\,000$. These different results suggest that the energy losses occurring in the brass lids are not negligible; thus, we use the data obtained in the cavity closed by MgB_2 lids to determine the mw surface resistance.

At fixed frequencies, we have measured the loaded quality factor and the coupling coefficients as a function of the temperature; from these results and by the same procedure used for the data in Fig. 5, we have determined the unloaded quality factor and, using (3), the mw surface resistance R_s of the MgB_2 material as a function of the temperature. The results obtained in the homogeneous MgB_2/MgB_2 cavity with MgB_2 lids at the fundamental mode are reported in Fig. 6. As shown, Q_U remains greater than 10^4 up to about 30 K and reduces by a factor of about 50 when the superconductor goes into the normal state.

At this point, we can estimate the error done by neglecting the contribution of the dielectric loss of the PTFE cups. The value of $\tan\delta$ reported in the literature for PTFE at $T = 1.3$ K and $f = 6.5$ GHz is 2×10^{-6} [34]; moreover, we have measured $\tan\delta$ at $T = 77$ K in the range of frequency 2–10 GHz obtaining values on the order of 10^{-4} [23]. Considering these values and those we obtain for $1/Q$ of Figs. 5 and 6, one can infer that, if PTFE fully fills the cavity, the contribution of the dielectric losses were about 10% of the wall losses. Since the PTFE stoppers cover the inner rod for about 10% of the rod length, neglecting their contribution, we overestimate R_s for a few percent, i.e., of the same order of the experimental uncertainty.

Fig. 7 shows the temperature dependence of the mw surface resistance extracted from the experimental data obtained in the MgB_2/MgB_2 coaxial cavity, with MgB_2 lids, at the first three resonant modes. The results relative to the mode resonating at 11 GHz are not reported here since the resonance curve for this mode is noisy probably because it falls near the frequency limit of the NA. From the analysis of the results obtained in the different resonant modes, we have determined the frequency dependence of the mw surface resistance at fixed temperatures. Our results showed that the $R_s(f)$ curves follow an f^n law, where n decreases on increasing the temperature. The inset in Fig. 7 shows the temperature dependence of n, which varies from $n \approx 2$, at $T = 4.2$ K, down to $n \approx 0.6$ in the normal state.

The frequency dependence of the mw surface resistance of MgB_2 has not been comprehensively investigated; in the literature, there are only few papers concerning results obtained mainly in films [35], [36]. To our knowledge, $R_s(f)$ of bulk samples has been investigated in the range of frequency

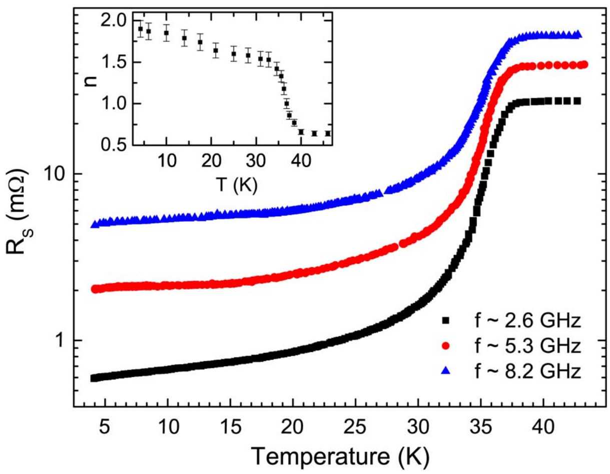

Fig. 7. Temperature dependence of the mw surface resistance determined from the results obtained in the homogeneous MgB_2/MgB_2 cavity closed by MgB_2 lids, for three different frequencies. (Inset) Temperature dependence of the exponent n obtained by fitting the $R_s(f)$ curves, at fixed temperatures, with the f^n law.

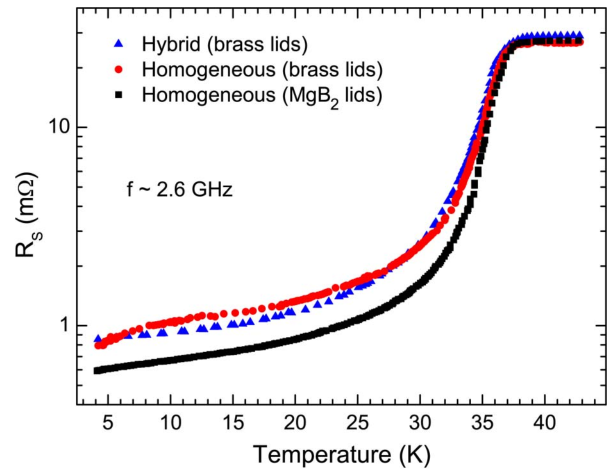

Fig. 8. Comparison among the results obtained for the mw surface resistance from the measurements performed by the three investigated cavities at the fundamental TEM mode.

10–100 MHz by Dmitriev *et al.* [37]. We would like to remark that the results shown in the inset in Fig. 7 have been obtained by fittings performed with only three frequency values, which may give rise to large uncertainties; hence, we think that the frequency dependence of R_s of our MgB_2 material has to be confirmed by investigating a longer rod in order to have a larger number of resonant modes in the same frequency range. The investigation of a longer rod is in progress and will be discussed elsewhere; nevertheless, the results we obtained in the superconducting state are consistent with those reported by Dmitriev *et al.* at lower frequency; on the contrary, in the normal state, we obtained frequency dependence closer to the expected one with respect to the linear dependence obtained by Dmitriev *et al.*

The values of the residual surface resistance, obtained extrapolating the low temperature data to $T = 0$ K, are 0.5 mΩ at 2.6 GHz, 2 mΩ at 5.3 GHz, and 5 mΩ at 8.2 GHz. They are of the same order of those measured in the first MgB_2 films [35] but higher than those obtained in more recently prepared MgB_2 films [9], [36], [38], [39]. Considering that we have built the whole cavity using bulk materials of large dimensions, the values of R_s we obtained at temperatures achievable with modern cryocoolers are satisfactory, although not competitive with the ones obtained in the best MgB_2 films [39]. This, at present, hinders the use of bulk MgB_2 to build cavities for particle accelerators. However, other applications such as filters for wireless base stations may take advantage of using bulk MgB_2 coaxial cavities at temperatures of 20 K–30 K.

The same type of measurements done in the homogeneous cavity with MgB_2 lids has been performed in both the homogeneous cavity with brass lids and in the hybrid MgB_2/Cu cavity. In the homogeneous cavity, changing the lids we have obtained results visibly different only in the fundamental mode, resonant at about 2.6 GHz, particularly at low temperatures (see, for example, Fig. 5). At higher frequencies, the differences are on the order of the experimental uncertainty. This can be understood considering that in normal metal, R_s follows the $\sqrt{f}$ law, whereas in MgB_2 we have found more than linear frequency dependence in the superconducting state. Therefore, the energy losses occurring in the brass lids affect the results primarily at low frequencies and low temperatures.

The quality factor of the hybrid MgB_2/Cu cavity is lower than that obtained in the homogeneous MgB_2/MgB_2 cavity because of the higher energy losses occurring in the outer copper-cylinder walls; for the fundamental TEM mode, resonating at about 2.6 GHz, we obtained $Q_U \approx 12\,000$ at $T = 4.2$ K; it reduces by a factor of 10 when the inner MgB_2 rod goes into the normal state. The analysis of data obtained from the hybrid cavity to deduce the mw surface resistance of the inner MgB_2 rod turned out to be more complex; indeed, it is necessary to use (2), which involves also the microwave surface resistance of the outer Cu cylinder. To this aim, we have assembled a coaxial cavity in which the MgB_2 rod has been replaced by a Cu rod of the same dimensions; we have investigated the mw response of the Cu cavity as a function of the temperature and determined the microwave surface resistance of the copper as a function of the temperature. Successively, using (2), we have determined the mw surface resistance of the inner rod.

Fig. 8 shows a comparison among the results of $R_s(T)$ of the MgB_2 material obtained by the three investigated cavities. As shown, we obtain very similar results by the hybrid cavity and the homogeneous cavity closed with brass lids; the little disagreement can be ascribed to the different sensitivities achieved with the two analysis methods. This result highlights that, although the cylinder and the rod of MgB_2 have been produced using different placements of the Mg and B reactants inside the steel container, the materials comprising the rod and the cylinder have very similar properties. Instead, comparing the results obtained with the homogeneous cavity closed by the two different pairs of adapters, one can note that the main differences occur in the superconducting state far from T_c. It is worth noting that, since it is not possible to quantify the energy losses occurring at the surface of the adapters, the results that better describe $R_s(T)$ of the MgB_2 material used to build the cavities are probably those obtained by the homogeneous cavity closed with MgB_2 lids that, for sure, dissipate less than the brass lids.

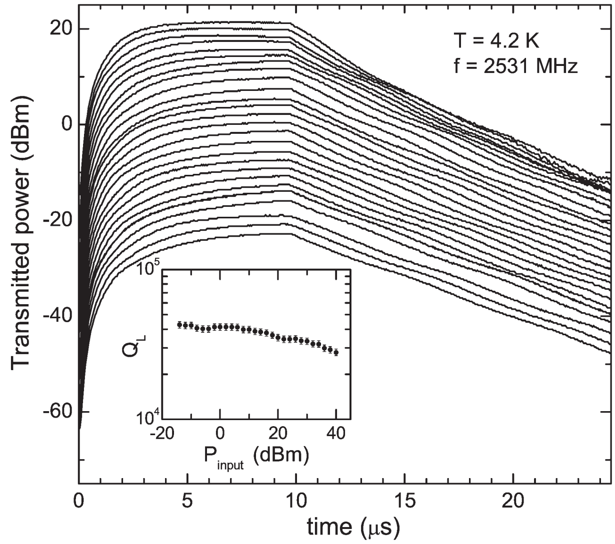

Fig. 9. Time response of the homogeneous cavity to an mw pulse, for different levels of the effective input peak power starting from (lower line) −14 dBm to (upper line) 40 dBm. Pulsewidth ≈10 μs. (Inset) Power dependence of the loaded quality factor determined measuring the decay time of the transmitted power.

B. Results as a Function of the Input Power

It is well known that the main factor limiting the use of cuprate superconductors in mw devices is the occurrence of nonlinear effects, which manifest themselves with an increase in the mw surface resistance above a certain threshold of input power. We have tested the homogeneous cavity with MgB_2 lids at different input power levels, in the fundamental TEM mode and at $T = 4.2$ K. The measurements have been performed using the MgB_2 adapters because, in this case, we obtained the highest quality factor. For these measurements, the cavity is immersed in the liquid He and fed by a train of mw pulses with pulsewidth of 10 μs, pulse repetition rate of 10 Hz, and maximum input peak power of 44 dBm. Fig. 9 shows the time response of the cavity during and soon after an mw pulse, at different values of the effective input peak power, from −14 to 40 dBm. The effective input power inside the cavity has been calculated, taking into account both the attenuation of the excitation line and the power reflected through the excitation port at the resonant frequency of the fundamental mode. The decay time of the transmitted power allowed us to determine the loaded quality factor as $Q_L = 2\pi f \tau$; the inset shows the power dependence of Q_L.

The inset in Fig. 9 highlights that, within the experimental uncertainty, the quality factor does not depend on the input power up to about 10 dBm and decreases less than a factor of 2 in the whole range of power investigated. This variation is much smaller than that detected in MgB_2 films [38], in which the nonlinearity onset has been detected at $P_{\text{in}} \approx -10$ dBm. The different behavior of bulk and films can be ascribed to the fact that, because of the small cross-sectional areas for current flow in films, high current densities are present at the film edges even at relatively low input power levels, enhancing nonlinear effects.

From the measured Q_L, we have determined Q_U and the mw surface resistance as previously explained. In Fig. 10, solid

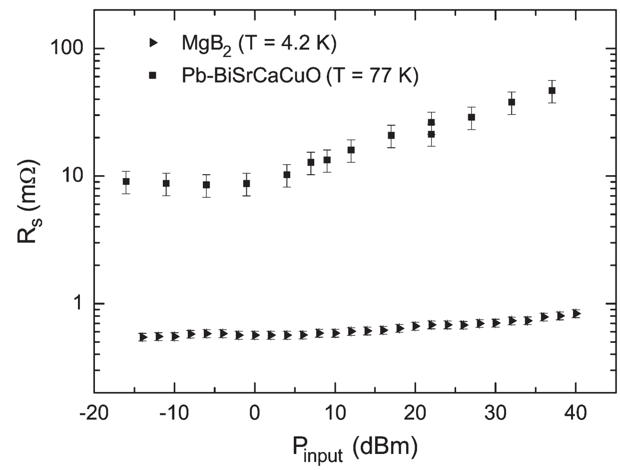

Fig. 10. Power dependence of the mw surface resistance of the MgB_2 material by which (triangles) the homogeneous cavity is done. For a comparison, we have reported the results obtained with a Pb–BiSrCaCuO rod inserted in (squares) a coaxial cavity with outer Cu tube at approximately the same frequency [23].

triangles represent the R_s values as a function of the effective input power, obtained at $T = 4.2$ K in the fundamental mode. For comparison, we have reported, as solid squares, the results obtained with a rod of Pb–BiSrCaCuO ($T_c \approx 110$ K) inserted in a coaxial cavity with outer Cu cylinder at approximately the same frequency [23].

The mw surface resistance of Pb–BiSrCaCuO is about 20 times greater than that of MgB_2, and the power dependence is more enhanced; this is most likely due to the weak link effects at grain boundaries [2], [3]. On the contrary, it is already established that, in MgB_2, only a small number of grain boundaries act as weak links, reducing energy dissipation and nonlinear effects [11]–[13].

From the values of the effective input power P_{in}, it is possible to calculate the peak value of the mw magnetic field inside the cavity, which for this mode falls at the middle point of the inner rod, obtaining for the homogeneous cavity [1]

$$H_{\text{mw}} = \sqrt{\frac{2P_{\text{in}}}{\pi a^2 \ell R_s (1/a + 1/b)}} \quad (4)$$

where ℓ is the length of the inner rod.

Although the ranges of the input peak power at which the results in Fig. 10 have been obtained are nearly the same for the two materials, the values of H_{mw} are different. This is due mainly to the different values of R_s of Pb–BiSrCaCuO and MgB_2, as well as, even if in a minor extent, to the slightly different dimensions. The results relative to the Pb–BiSrCaCuO rod have been obtained in the range $H_{\text{mw}} = 0.06$–13 Oe, and the onset of nonlinearity falls at $H_{\text{mw}} \approx 0.6$ Oe [23]. Due to the lower R_s value of the MgB_2 material, the maximum value of the peak magnetic field achieved at the maximum power level is about 100 Oe, and the slight variation of R_s starts at $H_{\text{mw}} \approx 12$ Oe (corresponding to $P_{\text{in}} = 20$ dBm). The maximum peak magnetic field we achieved with the homogeneous cavity is smaller but of the same order of magnitude than those achieved in previous investigations in MgB_2 bulk and films [39], [40]; even in our MgB_2 material, the mw surface resistance weakly depends on the mw field, as already highlighted in [39] and [40].

V. Conclusion

The aim of this paper was to do a feasibility study in using bulk MgB_2 to manufacture coaxial cavity resonators and understand how to couple it to the external line. We have investigated the mw response of coaxial cavity resonators built using MgB_2 bulk superconductor produced by the Mg-RLI. We have assembled two different coaxial cavities, i.e., a hybrid cavity, constituted by an outer Cu tube and an inner MgB_2 rod, and a homogeneous cavity using MgB_2 both for outer conductor and inner rod. Both cavities are about 60 mm long, with an external diameter ≈ 20 mm; the inner MgB_2 rod is the same for the two cavities and has a diameter of 3.8 mm and a length of 45 mm. The mw properties of the homogeneous MgB_2/MgB_2 cavity have been investigated closing the external cylinder with two different pairs of lids, i.e., one made of brass and another made of MgB_2.

In the frequency range investigated, i.e., 1–13 GHz, both cavities exhibit four resonant modes; the highest quality factor has been obtained in the fundamental TEM mode, resonating at ≈ 2.6 GHz. At $T = 4.2$ K and at the fundamental mode, the unloaded quality factor of the hybrid cavity is about 12 000; in the homogeneous cavity, we have obtained $Q_U = 50\,000$ with the brass lids and $Q_U = 65\,000$ with the MgB_2 lids. The quality factors maintain nearly the same values up to temperatures on the order of 30 K. At low input power levels, from the analysis of the resonance curves in the different resonant modes, we have determined the temperature dependence of the mw surface resistance of the MgB_2 materials at fixed frequencies and the frequency dependence of R_s at fixed temperatures. By a pulsed mw technique, we have measured the power dependence of R_s, at $T = 4.2$ K and $f \approx 2.5$ GHz, up to input peak power of 40 dBm, corresponding to a peak value of the mw magnetic field of about 100 Oe. We have highlighted that R_s of our MgB_2 material does not depend on the input power up to about 10 dBm and increases less than a factor of 2 on further increasing the input power of 30 dB. Our results show that bulk MgB_2 materials produced by the Mg-RLI are suitable to assemble coaxial cavity resonators with reduced nonlinear effects with respect to cuprate superconductors and to some MgB_2 films.

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