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# Dependence of Transport-Current Losses in $MgB_2$ Superconducting Wire on Temperature and Frequency

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***Abstract*—AC losses of a monofilamentary $MgB_2$ wire in a self-field are experimentally evaluated at several temperatures and frequencies. The alternating transport currents are applied to the straight sample wire, and the AC losses are observed electrically with a lock-in amplifier. The temperature of the sample wire was adjusted by a conduction cooling with gaseous helium, and the stability was below $\pm$0.1 K near a fixed temperature. The temperature dependence of the transport-current losses was roughly expained with a theoretical expression based on the Bean model, though the experimental results of the transport-current losses slightly depend on the frequency.**

***Index Terms*—AC loss, alternating transport current, lock-in amplifier, magnesium-diboride monofilamentary wire.**

## I. Introduction

THE hydrogen is one of the promising energy mediums in the near future because the oxidization of hydrogen for energy use yields only water as a by-product. In order to utilize the hydrogen stably and safely, the total system for production, transportation, storage, and transfer of the hydrogen has to be established as important infrastructures for sustainable society. Since the mass density of hydrogen is small, however, the effective treatment of hydrogen would be required especially in the stages of transportation and storage. Hence the use of liquid hydrogen would be better than compressed hydrogen because the density of the former is much larger than the latter [1].

In the beginning of the 21st century, a new metallic superconductor of magnesium-diboride ($MgB_2$) was discovered successfully, and this material has the critical temperature of 39 K [2]. Although many kinds of $MgB_2$ superconducting wires with metal sheaths have been fabricated up to now, the critical current densities of the present $MgB_2$ wires at 20 K near the boiling temperature of liquid hydrogen at atmospheric pressure have decreased drastically in an external magnetic field of a few teslas [3]. This means that the present $MgB_2$ wires would be suitable for applications in low magnetic fields. Level sensors for the liquid hydrogen with some kinds of $MgB_2$ wires have been investigated as one of the low-field applications [4]–[11]. Furthermore, a fully superconducting motor to drive a cryogenic electric pump for circulation or transfer of the liquid hydrogen has also been proposed [12]. Since both the $MgB_2$ superconducting windings for rotor and stator in the motor are located inside iron cores, the windings are scarcely exposed to the external magnetic field, and therefore the self-fields due to currents flowing in the windings themselves become dominant. The three-phase alternating currents are supplied to the stator winding in the proposed motor to generate a rotating magnetic field inside, so that a detailed understanding of AC loss properties in the $MgB_2$ windings is one of the key factors to realize the cryogenic superconducting pump although the AC loss measurements of various kinds of $MgB_2$ wires have been carried out so far [13]–[15].

In this study, the AC losses in an $MgB_2$ sample wire carrying alternating transport currents are experimentally evaluated in several temperatures and frequencies. The obtained results are also compared with an conventional theoretical expression based on the Bean model [16]–[18] to understand the dependence of the transport-current losses on the temperature and frequency.

## II. Properties of Sample Wire

The specifications of an $MgB_2$ sample wire are listed in Table I, and Fig. 1 shows the cross-sectional photograph of the wire. The mono-cored $MgB_2$ superconductor is surrounded by niobium, and a copper metal is located in their outside. The diameters of wire and filament are 0.8 mm and 0.555 mm, respectively, and the outer diameter of niobium is 0.685 mm.

The experimental results of critical currents of the $MgB_2$ sample wire are plotted in Fig. 2. Fig. 2(a) shows the dependence of the critical currents of the wire immersed in liquid helium with the external applied magnetic field. The critical current in the self-field at 4 K was 534 A. The critical currents rapidly decrease with increasing of the external magnetic field.

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TABLE I SPECIFICATIONS OF MAGNESIUM-DIBORIDE SAMPLE WIRE

| | |
|---|---|
| Structure | $MgB_2$/Nb/Cu |
| Number of filament | 1 |
| Diameter of wire | 0.8 mm |
| Diameter of filament | 0.555 mm |
| Outer diameter of Nb | 0.685 mm |
| Critical currents in self-field | 534 A (4 K) |
| | 192 A (26.4 K) |
| | 101 A (30.3 K) |

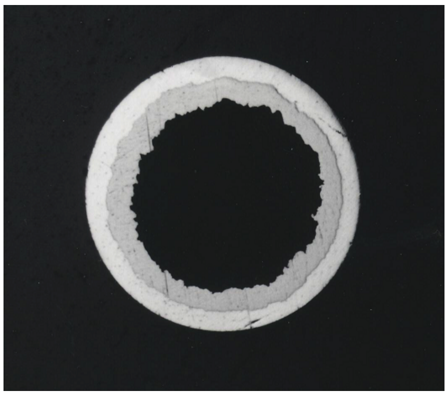


Fig. 1. Cross-sectional photograph of $MgB_2$ sample wire.

Fig. 2(b) shows the temperature dependence of the self-field critical currents. The solid line represents an approximated curve for the experimental results [19]. By using this approximated curve, the critical currents at the temperatures of 26.4 K and 30.3 K, at which the AC loss measurements were carried out, can be estimated as 192 A and 101 A, respectively.

## III. AC LOSS MEASUREMENTS

Let us consider a method to measure AC losses of a round wire with infinite length in the $z$-direction. When an alternating transport current $I_t$ is applied to this wire with a radius $R$, an uniform azimuthal magnetic field $H_\theta$ on the surface of the wire is given by

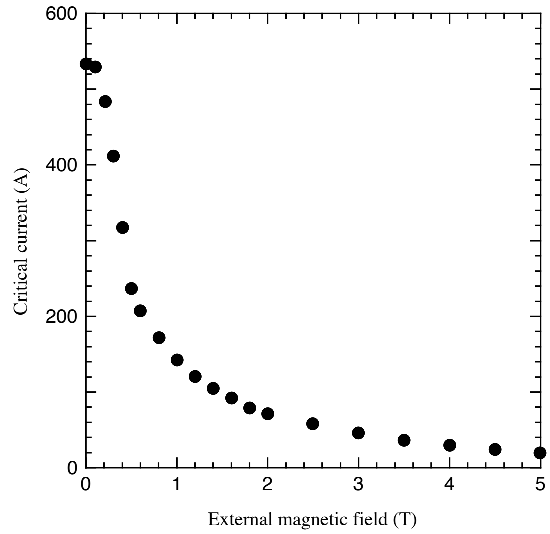
$$H_\theta = \frac{I_t}{2\pi R} \tag{1}$$

from Ampère's law. On the other hand, an uniform electric field $E_z$ on the surface of the wire is expressed by

$$E_z = \frac{V_s}{\ell} \tag{2}$$

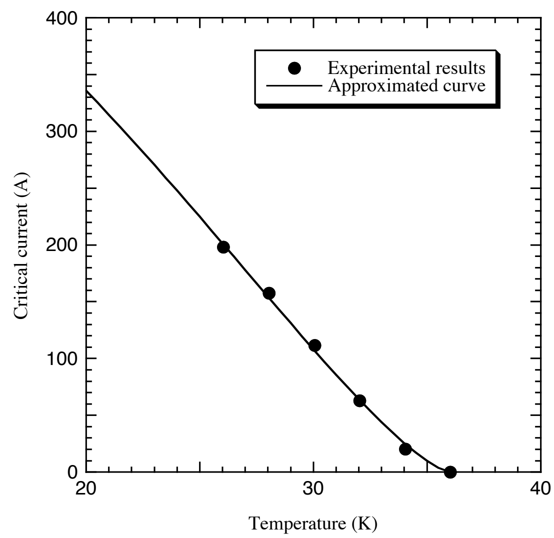
with the voltage drop $V_s$ and the length $\ell$ between a pair of potential taps attached to the wire. If a closed surface S on a cylinder as a part of the wire between the potential taps is focused on, the normal components of Poynting's vector on the both-side circular surfaces are equal to zero because the magnetic and electric fields have only the azimuthal and axial components, respectively. Therefore, the AC loss $Q$ per unit length per cycle can be obtained as

$$Q = -\frac{1}{\ell}\oint \mathrm{d}t \oint_{\mathrm{S}} (\boldsymbol{E}\times\boldsymbol{H})\cdot \mathrm{d}\boldsymbol{S} = \frac{1}{\ell}\oint V_s I_t \,\mathrm{d}t \,. \tag{3}$$





(a)





(b)

Fig. 2. Experimental results of critical currents of $MgB_2$ sample wire for (a) field dependence at liquid helium temperature and (b) temperature dependence in self-field [19].

Equation (3) is well known as the expression to evaluate the transport-current loss with a "four-probe method" or a "resistive method" for the straight wire.

When the alternating transport current $I_t$ has an amplitude $I_m$ and an angular frequency $\omega$ as

$$I_t = I_m \cos\omega t \,, \tag{4}$$

the voltage $V_s$ between the potential taps can be expressed generally with the Fourier series,

$$V_s = \sum_{k=1}^{\infty} \left(V_k' \cos k\omega t + V_k'' \sin k\omega t\right), \tag{5}$$

where $V_k'$ and $V_k''$ $(k = 1, 2, \cdots, \infty)$ are the Fourier coefficients. By substituting Eqs. (4) and (5) for Eq. (3), the AC loss $Q$ becomes

$$Q = \frac{1}{\ell}\frac{\pi V_1' I_m}{\omega} = \frac{1}{\ell}\frac{V_1' I_m}{2f}, \tag{6}$$

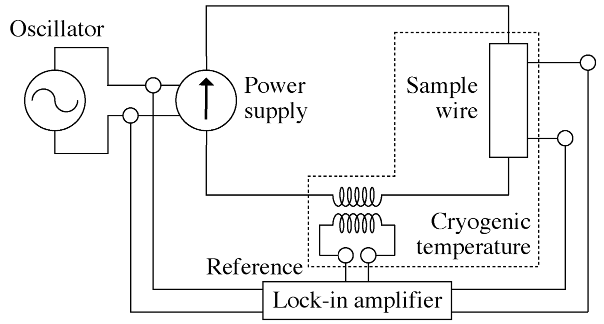



Fig. 3. Schematic diagram of electric circuit for measurement of transport-current loss.

where $f$ is the frequency. It can be seen in Eq. (6) that the transport-current loss can be estimated if only the fundamental $V_1'$ in-phase with the applied current is obtained, and thus a lock-in amplifier has been used widely so far to measure the transport-current losses in straight superconducting wires.

Fig. 3 shows a schematic diagram of electric circuit for the AC loss measurement. The output current in a power supply was controlled with a sinusoidal waveform oscillator. The reference signal for the lock-in amplifier was obtained directly from the output of the oscillator, and the phase for the reference was adjusted with a pickup coil for applied current in advance to measure the in-phase component in the voltage drop between a pair of potential taps attached to the sample wire. The effective length of the sample wire was 54 mm, and the distance between the potential taps was 10 mm. Both the sample wire and the pickup coil for current were located in the cryogenic environment. The sample wire was cooled indirectly by the thermal conduction with the gaseous helium whose temperature was suitably controlled in advance. The stability at a fixed temperature was less than $\pm 0.1$ K. No external magnetic field was applied to the sample wire.

Fig. 4 shows the experimental results of transport-current losses in the sample wire at the temperature of 26.4 K or 30.3 K and the frequency of 50 Hz or 100 Hz. The amplitude $I_m$ of applied current in the horizontal axis is normalized with the critical current $I_c$ of the wire at each temperature shown in Table I as $i = I_m/I_c$. The solid and dashed lines represent theoretical curves for the transport-current loss in the round wire based on the Bean model [16]–[18] given by

$$Q = \frac{\mu_0 I_c^2}{\pi}\left[(1-i)\ln(1-i) + \frac{(2-i)\,i}{2}\right]. \quad (7)$$

The experimental results of AC losses are a little bit larger than the theoretical curves. However, both the results at a fixed current amplitude present the decrease in the loss with the temperature rise because of the reduction of the critical current.

The dependence of the transport-current losses at fixed current amplitudes on the frequency is plotted in Fig. 5, where the closed symbols represent the experimental results at 26.4 K and the open symbols are for 30.3 K. The AC losses slightly increase with the frequency, and this might be due to the effect of the outer sheath in the $MgB_2$ sample wire.

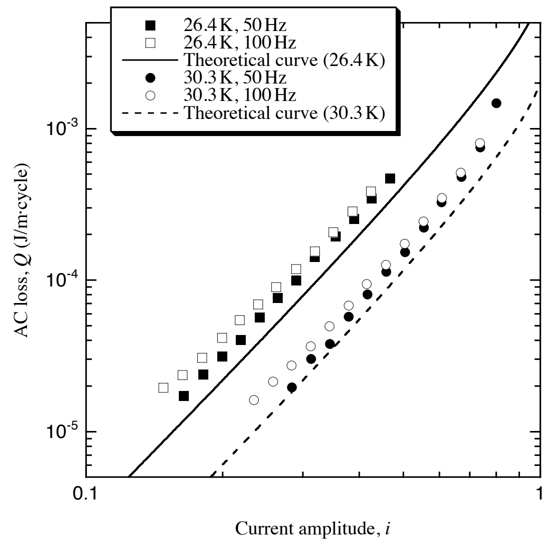



Fig. 4. Dependence of transport-current losses in $MgB_2$ sample wire on current amplitude.

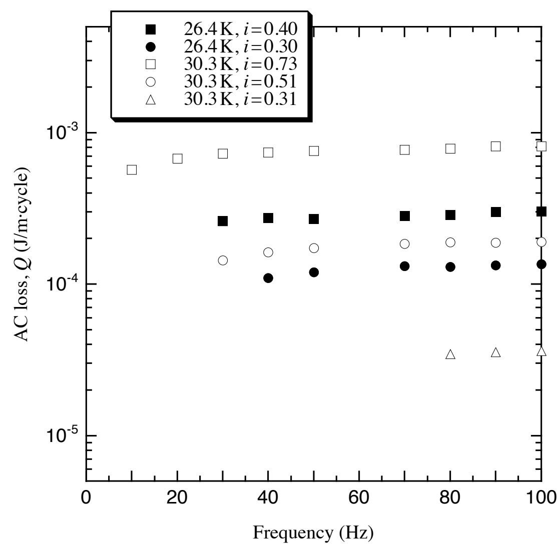



Fig. 5. Dependence of transport-current losses in $MgB_2$ sample wire on frequency.

## IV. CONCLUSION

The AC losses of the mono-cored $MgB_2$ wire with the alternating transport currents in the self-field were measured by means of the regular technique with the lock-in amplifier. The temperature of the sample wire was controlled indirectly with the flow of the cryogenic helium gas, and the frequency of the current applied to the sample wire was varied from a few tens hertz to a hundred hertz. The experimental results of transport-current losses at the fixed temperatures were a little bit larger than those estimated from the theoretical expression for the Bean model with the corresponding critical currents of the wire. Additionally, the transport-current losses at the constant temperature and current amplitude were also dependent slightly on the frequency. The further investigations with numerical calculations or theoretical considerations would be required for the next step in order to understand the properties of AC losses obtained from the experiments in detail.

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