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ORIGINAL PAPER

Influences of Ferromagnetic Substrate on Microwave Surface Resistance of Type-II Superconductors

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Abstract The influence of a ferromagnetic substrate on microwave surface resistance of high-temperature superconductors is numerically studied through finite element method computations. For a superconductor with a ferromagnetic substrate underneath, it is observed that an increase in ferromagnet susceptibility results in more shielding of the superconductor from the influence of external magnetic field and, in turn, a fall in microwave surface resistance. The effect saturates with higher susceptibilities where a plateau is reached in the surface resistance curve. As a comparison, coating superconductor with U-shaped ferromagnets on two sides is also considered where an ordinary hysteresis curve in terms of microwave surface resistance is observed for a non-magnetic coating. In contrast, a highly ferromagnetic coating with a relative permeability of 1000 gives rise to an unusual hysteresis behavior.

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1 Introduction

Superconductor studies have focused on their technological applications for a long time. As a result, significant advances have been witnessed regarding high-temperature superconductors which are more convenient in terms of critical temperature, whereas numerous applications have come into life such as coils, fault-current limiters, antennas, and filters with different geometries [1–6]. In a majority of these applications, geometrical parameters have been used to optimize fundamental superconductor parameters such as critical current density and external magnetic field penetration. During the last decade, superconductors have been considered along with ferromagnetic substrates which can be used in optimization of their properties such as critical current density distribution.

The fact that coating edges of a superconducting stripe with a ferromagnetic material gives rise to an increase in critical current density was first observed experimentally by Alamgir et al. [7]. This result was later numerically analyzed by Gömöry et al. [8]. On the other hand, as similar experimental alternating current (AC) loss studies conducted for YBCO superconductors [9, 10] reported different results than the calculations by Norris et al. [11], investigation of the influences of a ferromagnetic substrate on AC losses has gained prime importance. In this respect, starting from the procedure proposed by Campbell et al. [12],

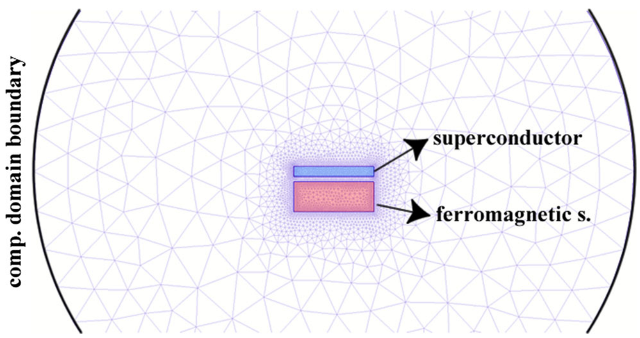


Fig. 1 Schematic illustration of superconductor with a ferromagnetic substrate and meshing of computational domain

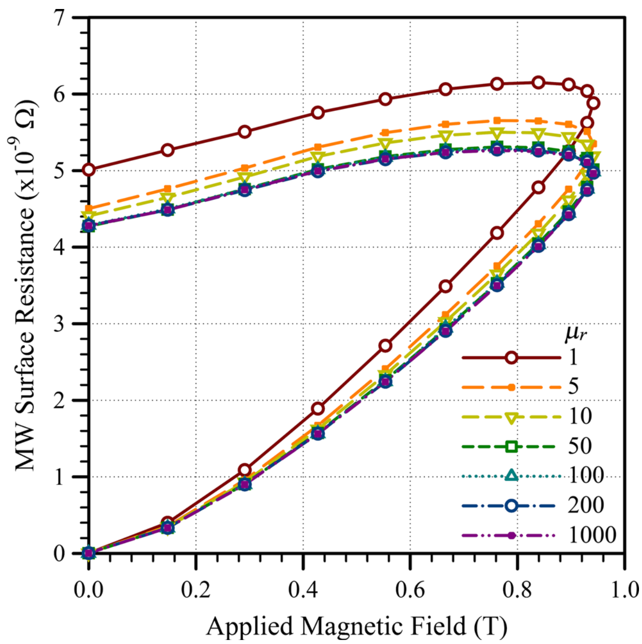


Fig. 2 Dependence of microwave surface resistance on external magnetic field in the presence of a ferromagnetic substrate. The simulation parameters are as in Table 1

Gömöry et al. [13] studied the influence of ferromagnetic substrate on AC losses. These studies were, later, expanded for different types of coating [14–16] and geometries [17, 18]. Furthermore, vortex states and pinning properties for superconductor-ferromagnetic structures or ferromagnetic particles, dots, and pillars in superconductors have drawn tremendous interest [19–23].

Incorporation of ferromagnetic materials in superconductors might facilitate numerous applications, which can be very suitable for magnetic shielding. Studies which take into account new parameters in order to be able to model some of these are required. In this work, we focus on simple binary structures and calculate microwave (MW) surface resistance, which is an important parameter with respect to utilization of superconductors in electronics. We carried out numerous calculations for varying applied magnetic field and various geometrical designs and different magnetic permeability values of the ferromagnetic substrate.

2 Results and Discussion

The governing equations which facilitate calculation of microwave surface resistance within the framework of the critical-state model proposed by Bonura et al. [24, 25] through the theory proposed by Coffey and Clem [26–28] are the same as those which can be found in other studies [24, 25, 29, 30]. In the present work, a method based on the finite element method (FEM) is used, which is similar to the approach employed by Gömöry et al. [31]. The governing

Table 1 List of physical and geometrical parameters used in FEM computations

Symbol	Unit	Description	Value
I_c	A	Critical current	75
J_{c0}	A/m^2	Critical current density at $T = 0$ K	$I_c / (w_{sc} \times h_{sc})$
A_n		Scaling parameter	1×10^{-9}
λ_0/δ_0		Ratio of London penetration depth to normal-fluid skin depth at $T = 0$ K	0.02
T/T_c		Ratio of absolute to critical temperature	0.5
ω_c/ω		Ratio of the working to depinning frequency	1
B_{c20}	T	Upper critical magnetic field	$135B*$
$B*$	T	Full penetration field	$\mu_0 J_{c0} h_{sc} / 2$
B_0	T	The scaling parameter for the field dependence	0.032
h_{sc}	µm	Thickness of superconducting strip	0.5
w_{sc}	µm	Width of superconducting strip	10
h_{FM}	µm	Thickness of ferromagnetic substrate	2.5
w_{FM}	mm	Width of ferromagnetic substrate	10
μ_r		Relative permeability of ferromagnetic substrate	1/5/10/50/100/200/1000

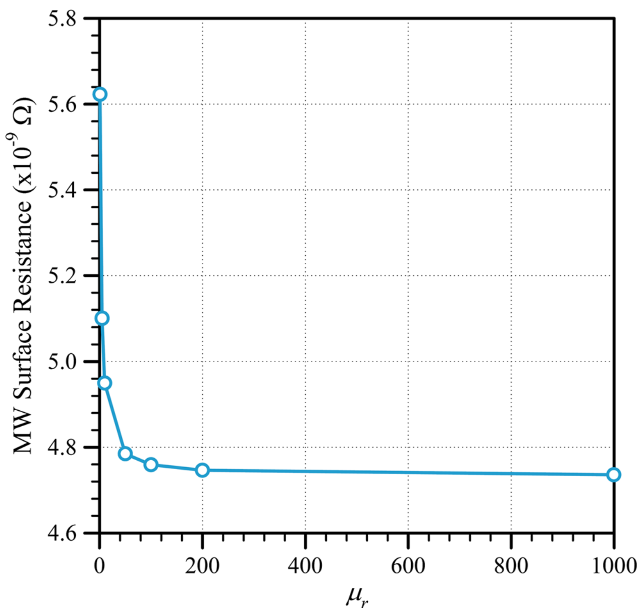


Fig. 3 Relationship between the microwave surface resistance and relative permeability for the maximum value of applied field in Fig. 2

equation for the prediction of current density through FEM calculations is

$$\vec{\nabla} \times \left(\frac{1}{\mu_0} \vec{\nabla} \times \overrightarrow{A} \right) = \vec{J} \tag{1}$$

where $\overrightarrow{A}$ is a magnetic vector potential and $\mu_0 = 4\pi \cdot 10^{-7}$ Hm^{-1} is the magnetic permeability of free space. Although the parallel component of field distribution is not influential on the magnitude of the microwave surface resistance, we used critical current density to take into account the anisotropy of field dependency as follows:

$$J_c(B) = \frac{J_{c0}}{\left(1 + \frac{\sqrt{k^2 B_x^2 + B_y^2}}{B_0}\right)^{\beta}} \tag{2}$$

where J_{c0} is the current density under zero applied magnetic field, B_0 is the scaling parameter for the field dependence, while β is its exponent, and k is the anisotropy quotient ($k = 1$ for an isotropic material). A step function form of J_s is used for evaluation of current and field distributions inside the superconductor when the external field is increasing:

$$J_{s,\mathrm{incr}}(x, y) = J_c \tanh \left(\frac{-A(x, y)}{A_n} \right) \tag{3}$$

In contrast, for the decreasing field, one can write

$$J_{s,\mathrm{decr}}(x, y) = J_c \tanh \left(\frac{A_p(x, y) - A(x, y)}{A_n} \right) \tag{4}$$

where J_c is the critical current density [17] and A_n is a properly adjusted scaling factor [12].

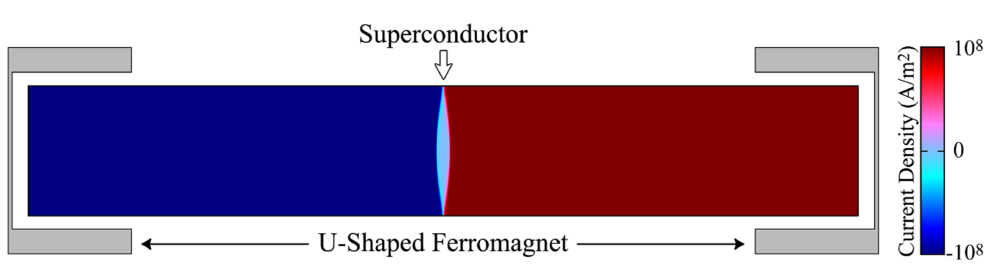
For calculating surface resistance using Coffey-Clem equations [26–28], some physical parameters such as the ratio λ_0/δ_0, the lower and upper critical fields, and the depinning frequency must be known. Moreover, in considering the critical-state effects by the model due to Bonura et al. [24, 25], it is also essential to know the B profile inside the sample. In this case, COMSOL Multiphysics software, which is a commercial implementation of FEM, can be employed to compute geometry-dependent field profile in the sample via its AC/DC module [32]. As an approximation, the width of our two-dimensional (2D) geometry is 10 µm and the ratio between the radius of computational domain and superconductor width is selected as 25/1 (Fig. 1).

Computational domain is divided into approximately 10^5 triangular elements, and a mesh with 50 elements across the layer thickness to obtain a finer meshing is employed. An estimation of the magnetic field distributions due to an applied magnetic field on the superconductor as a function of position is obtained through individual FEM computations. This step can be generalized for the whole applied field range using custom codes on MATLAB platform [33]. The physical and geometrical parameters employed in computations are provided in Table 1.

FEM computations with regard to different permeability values and geometrical design parameters are conducted. The fist simple geometrical design involves a superconducting stripe and a ferromagnetic substrate just underneath it (Fig. 1). Figure 2 presents the computational results for different permeability values of the ferromagnet.

Two features can be noticed in Fig. 2: First, the applied external magnetic field is smaller than the penetration field. This results in a concave shape of microwave surface resistance curve. Second, there is a decrease in surface resistance

Fig. 4 Demonstration of the distribution of current density inside a superconductor coated with U-shaped ferromagnets with μ_r = 1000 on both sides



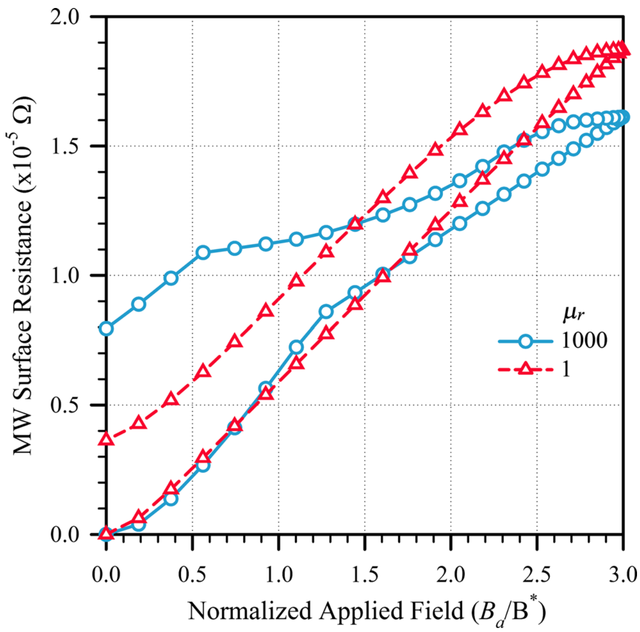


Fig. 5 Influence of coating the superconducting sample with U-shaped ferromagnetic materials on both sides, as in Fig. 4, on MW surface resistance. Simulation parameters different than those in Table 1 are $A_n = 3 \times 10^{-10}$, $B_0 = 0.5$, $h_{sc} = 25$ μm, $w_{sc} = 4$ mm, $h_{FM} = h_{sc}/5$ (edge thickness of ferromagnet), and $\mu_r = 1$ or 1000

with increasing relative permeability. This can be more easily seen in Fig. 3, in which variation of MW surface resistance with respect to permeability is depicted. It is clearly seen that increasing permeability shields the superconductor from the influence of external magnetic field and, in turn, gives rise to a fall in microwave surface resistance. This effect saturates with still increasing permeability, and eventually, a plateau is reached in microwave surface resistance (Fig. 3).

In addition to a superconducting sample grown on a ferromagnetic substrate, superconducting structures surrounded by U-shaped ferromagnetic materials have been extensively studied [8, 13, 14, 16]. In an anticipation that considering such a sample for microwave surface resistance calculations can give interesting results, FEM computations are conducted for the so-called horseshoe-shaped superconducting sample, as depicted in Fig. 4. Computational results for such a structure where $\mu_r = 1$ and $\mu_r = 1000$ are presented in Fig. 5.

Calculations for $\mu_r = 1$ indicate that the cover materials at both sides do not impose any magnetic properties (Fig. 5), as revealed by observation of ordinary hysteresis behavior. In contrast, an unusual behavior is apparent when the superconductor is covered by a U-shaped ferromagnet with $\mu_r = 1000$. In the case where the surface resistance at the maximum external magnetic field is considered, the sample surrounded with a ferromagnetic material is more efficient. In contrast, in terms of the surface resistance under the trapped field, non-ferromagnetic coating is more efficient. Although this is an interesting observation, we think that this can be due to the fact that the field trapped over the ferromagnetic domain can be larger than the applied field despite a decreasing field.

3 Conclusion

In conclusion, influences of ferromagnetic materials on microwave surface resistance of high-temperature superconductors were studied. Finite element method-based computations reveal that the presence of the ferromagnetic material acts to reduce the microwave surface resistance under maximum magnetic field. This, in turn, suggests that utilization of superconductors along with ferromagnetic materials can yield more efficient results in microwave applications.

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