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氏　　　名	高橋　圭太

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Realization of superconducting bulk magnets with higher magnetic field gradient to provide a quasi-zero gravity space on earth

学位論文要旨

Bulk superconductors such as (RE)BaCuO (RE: rare earth elements or Y) can be utilized as a so-called trapped field magnets (TFM) that can "trap" the magnetic fields over several Tesla by exploiting the flux pinning effect of Type-II superconductors. The trapped field can be sustained inside the bulk with its induced supercurrent quasi-permanently once it is magnetized and kept at a constant temperature; hence, can replace conventional magnets as a compact and strong magnet for potential applications. It is noteworthy that there is a limit in the trapped field enhancement according to the tripartite relation between Electromagnetic field, Temperature, and Mechanical stress as the brittle ceramic nature. For more practical design, it is also desirable for the magnetic source to provide such a strong magnetic field even in an open space outside the vacuum chamber other than to be lightweight and mobile as a desktop-type apparatus. In this sense, the author newly developed two hybrid-type TFMs called as a hybrid TFM lens (HTFML) which can generate a concentrated field higher than the trapped field, and a high gradient-type TFM (HG-TFM) which can provide a higher magnetic force with its refined field gradient product, $B_z{\cdot}dB_z/dz$. Including the introduction in chapter 1 and the conclusion in the last chapter 8, this Ph.D thesis summarizes six papers published since 2018 to 2021, relating to the development of the HTFML in chapter 2 to chapter 5, its applicational aspect for the magnetic separation in chapter 6, and another new concept of the HG-TFM in chapter 7. The concepts of such hybrid-type TFMs were first considered using a numerical simulation in an efficient way, and then the experimental validation was performed.

In chapters 4 and 5, the HTFML was validated experimentally. This exploits the "vortex pinning effect" of an outer bulk cylinder and the "diamagnetic shielding effect" of an inner bulk magnetic lens to generate a concentrated magnetic field higher than the trapped field from the outer TFM. This requires that, during the magnetizing process, the outer TFM cylinder is in the normal state ($T >$ superconducting transition temperature, T_c) and the inner magnetic lens is in the superconducting state ($T < T_c$) when the external magnetizing field is applied, followed by cooling to an appropriate operating temperature, then removing the external field. This is explored for two potential cases: 1) exploiting the difference in T_c of two different bulk materials ("case-1"), *e.g.*, MgB_2 (T_c = 39 K) and GdBaCuO (T_c = 92 K) or 2) using the same material for the whole HTFML, *e.g.*, GdBaCuO, but utilizing the same cryostat with different cooling loops that keep the outer bulk cylinder at a temperature above T_c. As a result, the HTFML could reliably generate a concentrated magnetic field B_c = 3.55 T with an external magnetizing field B_{app} = 2 T in the "case-1", and a higher B_c = 9.8 T with higher B_{app} = 7 T in the "case-2," respectively. These experimental results were consistent well with the numerical estimation results in chapter 2 and 3.

In chapter 6, it was predicted by numerical simulation that the HTFML device after the magnetization process with an applied field, B_{app} = 10 T, can generate the maximum of B_c = 11.4 T, as well as an ultra-high $B_z{\cdot}dB_z/dz$ over 3000 T^2/m, which can fulfill the requirement of the magnetic levitation of water drop as high as 1400 T^2/m.

In chapter 7, state-of-the-art numerical simulations were used to investigate the magnetic properties of the proposed HG-TFM in detail. In the modelling, slit ring bulks (slit-TFMs) are tightly stacked with TFM cylinders (full-TFMs), which is useful to improve the magnetic field gradient with its inverse field through the slits. A maximum $B_z{\cdot}dB_z/dz$ = 6040 T^2/m was predicted even by using the simpler conventional field-cooled magnetization (FCM) with B_{app} = 10 T at 40 K, which should be the highest value ever reported compared to any other magnetic sources. The HG-TFM has an advantage on the versatility, *e.g.*, a wider open space and its simple operation at one constant temperature.

These devices deserve to be unique that its superior magnetic properties and the versatility come from the refinement of the magnetizing method in contrast to conventional approaches that depend on the superconducting properties of the bulk itself. Now, since the prototype can be installed even in a laboratory scale and can provide the quasi-zero gravity space in an open space inside/outside the vacuum chamber, further applicational studies would be explored in a more practical setup towards the new industrial application such as protein crystallization and cell culture.