

Microwave Superconductivity

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(Invited Paper)

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ABSTRACT We give a broad overview of the history of microwave superconductivity and explore the technological developments that have followed from the unique electrodynamic properties of superconductors. Their low loss properties enable resonators with high quality factors that can nevertheless handle extremely high current densities. This in turn enables superconducting particle accelerators, high-performance filters and analog electronics, including metamaterials, with extreme performance. The macroscopic quantum properties have enabled new generations of ultra-high-speed digital computing and extraordinarily sensitive detectors. The microscopic quantum properties have enabled large-scale quantum computers, which at their heart are essentially microwave-fueled quantum engines. We celebrate the rich history of microwave superconductivity and look to the promising future of this exciting branch of microwave technology.

INDEX TERMS High-temperature superconductors, Josephson junctions, Quantum computing, SQUIDs, Superconductivity, Superconducting filters, Superconducting logic circuits, Superconducting materials, Superconducting microwave devices, Superconductive tunneling.

I. INTRODUCTION

The unique microwave properties of superconductors enable a remarkable range of novel applications and technologies. The low Ohmic losses of the superconducting state allow for extremely high efficiency and compact charged particle accelerators based on microwave resonant cavities with quality factors exceeding 10^{11} . The unique electrodynamic properties of superconductors enable low-dispersion transmission lines that preserve the integrity of extremely short electrical impulses. This, along with the macroscopic quantum properties of superconductors have enabled a family of radically new digital electronics based on magnetic flux quantization and the Josephson effect. The low-loss and nonlinear properties of superconductors create an ideal setting for demonstration of quantum phenomena such as entanglement and controlled quantum state evolution. Because microwave superconductivity is a key enabler for present and future quantum technologies, anyone trained in microwave engineering has entry level skills for this exciting new technology frontier [1]. My goal in this article is to give an overview of the remarkable microwave technologies uniquely enabled by superconductivity. I will also argue that the barrier to utilizing these “exotic”

technologies has been considerably lowered in recent years through the development of inexpensive and highly reliable cryogenic technology infrastructure.

This overview touches lightly on many fascinating topics. The technical detail (and rigor) is kept to a minimum in order to bring out the main trends in the development of superconductors for microwave applications. To delve deeper, the interested reader is advised to consult a number of helpful books, monographs, and articles on microwave superconductivity that have appeared in the recent past. The most comprehensive is probably the collected papers from a NATO Advanced Study Institute [2]. Other accessible but more specialized sources on microwave superconductivity include works on RF superconductivity for particle accelerator applications, [3], [4] Josephson junction dynamics, [5] electrodynamics of high-temperature superconductors, [6] analog superconducting microwave electronics, [7]–[10] high-frequency superconducting materials issues, [11] and early microwave measurements of superconductors [12].

This article begins with a review of the basic features that distinguish superconductors from ordinary metals. It then summarizes the key technical quantities that characterize the

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**Haiwen Liu, Baoping Ren, Xuehui
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Microwave Superconductivity H. Weinstock, Martin Nisenoff, 2001 Proceedings of the NATO Advanced Study Institute Millau France 29 August 10 September 1999 Electrodynamics of Solids and Microwave Superconductivity Shu-Ang Zhou, 1999-07-23 Die Elektrodynamik von Festkörpern ist ein interdisziplinäres angelegtes Thema zu dem elektromagnetische Phänomene mechanische Bewegungen und Verformungen sowie Wärmeleitungen in festen Stoffen gleichermaßen beitragen Dieses einführende und dennoch umfassende Lehrbuch zur Theorie der Elektrodynamik und Halbleitertechnik richtet sich an Physiker ebenso wie an Elektrotechniker Maschinenbauer und Studenten der einschlägigen Fachrichtungen 08 99

Handbook of Superconductivity David A. Cardwell, David C. Larbalestier, Aleksander Braginski, 2022-07-05 This is the last of three volumes of the extensively revised and updated second edition of the Handbook of Superconductivity The past twenty years have seen rapid progress in superconducting materials which exhibit one of the most remarkable physical states of matter ever to be discovered Superconductivity brings quantum mechanics to the scale of the everyday world Viable applications of superconductors rely fundamentally on an understanding of these intriguing phenomena and the availability of a range of materials with bespoke properties to meet practical needs While the first volume covers fundamentals and various classes of materials the second addresses processing of these into various shapes and configurations needed for applications and ends with chapters on refrigeration methods necessary to attain the superconducting state and the desired performance This third volume starts with a wide range of methods permitting one to characterize both the materials and various end products of processing Subsequently diverse classes of both large scale and electronic applications are described Volume 3 ends with a glossary relevant to all three volumes Key Features Covers the depth and breadth of the field Includes contributions from leading academics and industry professionals across the world Provides hands on familiarity with the characterization methods and offers descriptions of representative examples of practical applications A comprehensive reference the handbook is suitable for both graduate students and practitioners in experimental physics materials science and multiple engineering disciplines including electronic and electrical chemical mechanical metallurgy and others

Handbook of Superconducting Materials David A. Cardwell, David S. Ginley, 2003 **Superconducting Materials** Yassine Slimani, Essia Hannachi, 2022-05-03 This book presents an overview of the science of superconducting materials It covers the fundamentals and theories of superconductivity Subjects of special interest involving mechanisms of high temperature superconductors tunneling transport properties magnetic properties critical states vortex dynamics etc are present in the book It assists as a fundamental resource on the developed methodologies and techniques involved in the synthesis processing and characterization of superconducting materials The book covers numerous classes of superconducting materials including fullerenes borides pnictides or iron based chalcogen superconductors intermetallics alloys and cuprate oxides Their crystal structures and properties are described Thereafter the book focuses on the progress of the

applications of superconducting materials into superconducting magnets fusion reactors and accelerators and other superconducting magnets The applications also cover recent progress in superconducting wires power generators powerful energy storage devices sensitive magnetometers RF and microwave filters fast fault current limiters fast digital circuits transport vehicles and medical applications *100 Years of Superconductivity* Horst Rogalla, Peter H. Kes, 2011-11-11 Even a hundred years after its discovery superconductivity continues to bring us new surprises from superconducting magnets used in MRI to quantum detectors in electronics 100 Years of Superconductivity presents a comprehensive collection of topics on nearly all the subdisciplines of superconductivity Tracing the historical developments in superconductivity *High Temperature Superconductivity 2* A. V. Narlikar, 2004 In contrast to the research on the fundamental mechanism of High Temperature Superconductivity the recent years have seen enormous developments in the fabrication and application of High Tc Superconductors The two volumes of High Temperature Superconductivity provide a survey of the state of the technology and engineering applications of these materials They comprise of extended original research papers and technical review articles written by physicists chemists materials scientists and engineers all of them noted experts in their fields The interdisciplinary and strictly application oriented coverage should benefit graduate students and academic researchers in the mentioned areas as well as industrial experts Volume 1 Materials focuses on major technical advancements in High Tc materials processing for applications Volume 2 Engineering Applications covers numerous application areas where High Tc Superconductors are making tremendous impact TOC HTS Applications Present and Future Prospects Application Fields of High Temperature Superconductors The Application of High Temperature Superconductors in Brushless AC Machines Current Status of High TC Superconducting Bulk Rotating Electric Motors Application A Motor with High Temperature Superconducting Levitation and Its Vibration Control Levitation Applications of High Temperature Superconductors Fields and Forces from Superconductors and Permanent Magnets Trends of Applications to High Tc Superconducting Power Transformers in Japan Applications of High Tc Superconductors to Superconducting Magnetic Energy Storage SMES Unrivalled Sensitivity Squids in Nondestructive Testing DC Squid Magnetometers from YBa₂Cu₃O₇ d for Biomagnetic Applications HTS Applications Progress in Squid Microscopy and High Resolution Non Destructive Evaluation Vortex Matter and Superconducting Electronic Devices HTS Microwave Filters Properties Design and System Applications Response Analysis and Modeling of High Temperature Superconductor Edge Transition Bolometers High Temperature Superconducting Cables **High Temperature Superconductivity 2** Anant V. Narlikar, 2013-11-11 In contrast to research on the fundamental mechanisms of High Temperature Superconductivity in recent years we have seen enormous developments in the fabrication and application of High Tc superconductors The two volumes of High Temperature Superconductivity provide a survey of the state of the technology and engineering applications of these materials They comprise extended original research papers and technical review articles written by physicists chemists materials scientists

and engineers all of them noted experts in their fields The interdisciplinary and strictly application oriented coverage should benefit graduate students and academic researchers in the mentioned areas as well as industrial experts Volume 1 Materials focuses on major technical advancements in High Tc materials processing for applications Volume 2 Engineering Applications covers numerous application areas where High Tc superconductors are making tremendous impact On New Possibilities in Microwave Superconductivity Alberto Canabal,2009 *High-Temperature Superconducting Microwave Circuits and Applications* Haiwen Liu,Baoping Ren,Xuehui Guan,Pin Wen,Tao Zuo,2019-04-02 High temperature superconducting HTS materials are becoming more and more attractive in the context of designing RF microwave filters because of their lower losses and excellent performance This book focuses on the superconducting microwave filter and its application in modern communication It first presents the basic principles HTS materials and processing and then introduces several types of multi band HTS bandpass filter BPF discussing their properties and analyzing equivalent circuit models and their performances This book is a valuable resource for students and researchers who are interested in wireless communication and RF microwave design Microwave Superconductivity Harold Weinstock,2001 **Superconductivity and Its Applications** Hoi S. Kwok,David T. Shaw,1988 *High-Temperature-Superconductor Thin Films at Microwave Frequencies* Matthias Hein,1999-07-02 The book develops a comprehensive understanding of the surface impedance of the oxide high temperature superconductors in comparison with the conventional superconductor Nb3Sn Linear and nonlinear microwave responses are treated separately both in terms of models theories or numerical approaches and in terms of experimental results The theoretical treatment connects fundamental aspects of superconductivity to the specific high frequency properties The experimental data review the state of the art as reported by many international groups The book describes further the main features of appropriate preparation handling mounting and refrigeration techniques and finally discusses possible applications in passive and active microwave devices **Superconductivity** ,1992 **Microwave Analysis of Unconventional Superconductors with Coplanar-Resonator Techniques** Gianluca Ghigo,Daniele Torsello,2022-01-29 This book provides a thorough overview of methods and approaches to the experimental characterization of superconductors at microwave frequencies and includes a detailed description of the two main techniques both based on the use of coplanar waveguide resonators that the authors employed to investigate the properties of unconventional superconductors In the second part several case studies are described covering a large spectrum of materials and issues Particular emphasis is given to recent hot topics concerning iron based superconductors both of fundamental nature and relevant for applications The book is intended as a learning tool for researchers in the field and serves as a guide providing inspiring examples of the use of coplanar resonator techniques to address key topics in the field of unconventional superconductivity *Passive Microwave Device Applications of High Temperature Superconductors* M. J. Lancaster,1997 The first book on applications of high temperature superconductors in electrical engineering *Superconductivity* Werner

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