Microwave superconductivity
Part 1: History, properties and early applications

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Abstract—The 100th anniversary of superconductivity will be celebrated during 2011. As part of this celebration, a Special Session has been scheduled for IMS 2011 to commemorate this event and highlight the potential impact of superconductivity on electronic technologies, especially in the microwave and terahertz frequencies regimes. In this paper, Part 1, the history, properties and some early high frequency applications of superconductivity will be reviewed, while in Part 2, current and future applications will be discussed.

Index Terms—superconducting microwave devices, SQUIDs, superconducting filters, analog-to-digital convertors sensors, high-speed electronics, high temperature superconductors

I. INTRODUCTION

On 8 April 1911, in the Physical Laboratory of the Leiden University in Leiden, The Netherlands, Prof Heike Kamerlingh Onnes and his collaborators, Cornelis Dorsman, Gerrit Jan Fim, and Gilles Holst, were studying the electrical properties of pure materials in the temperature range near 4 kelvin, the temperature of liquid helium at atmospheric pressure. As the temperature of a pure mercury sample was lowered toward 3 kelvin, they observed that the resistance became “practically zero”. In a subsequent experiment on 23 May 1911, they cooled a mercury sample to 3 kelvin and again observed that the resistance was “practically zero”. As the temperature of the sample was slowly raised, near 4 kelvin, the resistance abruptly increased, by more than three orders of magnitude over a temperature interval much less than 0.1 kelvin. This new phenomena was initially called “supraconductivity” but was later change to “superconductivity” [1].

To recognize the importance of this discovery to electrical technology and to commemorate the 100th anniversary of the discovery of superconductivity by Prof. Kamerlingh Onnes and his collaborators, the IEEE has designated the event as a Milestone in Electrical Engineering and Computing and a Milestone Plaque was dedicated on 8 April 2011 in the building where the experiments were performed. See Fig. 1 [2].

In connection with the celebration of the centennial of superconductivity, and to commemorate the 100th anniversary of the discovery of superconductivity by Prof. Kamerlingh Onnes and his collaborators, the IEEE has designated the event as a Milestone in Electrical Engineering and Computing and a Milestone Plaque was dedicated on 8 April 2011 in the building where the experiments were performed. See Fig. 1 [2].

Fig. 1. Photograph of Milestone Plaque that was dedicated at the site where superconductivity was discovered.

II. A BRIEF HISTORY OF SUPERCONDUCTIVITY

For the first 50 years after its discovery, superconductivity remained a very exotic phenomenon. In the late 1950s, John Bradeen, Leon Cooper and Robert Schrieffer proposed a theory, [6], which is commonly referred to as the “BCS theory” which described, in great detail, the unique electrical and thermal properties of the superconducting state. For their pioneering work in developing their theory, they received the Nobel Prize in Physics in 1972.

During the first 75 years after the discovery of superconductivity in mercury, more than 5,000 elements, compounds and alloys were discovered to exhibit superconductivity at temperatures below about 23 K, including about one-half of the elements. In 1986, Bednorz and Mueller [7] discovered a class of oxide materials which were superconducting at temperatures above 23 K and other materials have been discovered subsequently with transition temperatures as high as 150 K. These materials can significantly reduce the cryogenic burden associated with the use of superconductors as these materials can be operated at temperature near and even above 77 K, the temperature of boiling liquid nitrogen at atmospheric pressure. Unfortunately, these “high temperature superconductors” (HTS) tend to be ceramic in nature and thus are relatively difficult to fabricate into useful configurations, such as cables and conductors. There are a large number of books and articles in the open literature that describe the status of both “low temperature superconductors” (LTS) and
III. PROPERTIES OF THE SUPERCONDUCTING STATE

There are a number of very unique properties of the superconducting state that enable the development of applications that cannot be realized using conventional electrical technologies.

1) Critical Temperature: The most commonly known property of the superconducting state is that a superconductor is characterized by a critical temperature, below which the material exhibits “zero” resistance. In the original experiments on mercury, the upper limit to the resistivity of mercury in the superconducting state was estimated to be about $10^{-6}$ that of the resistance at room temperature.

2) Persistent Current: If a current is induced in a totally superconducting loop, the current will continue to flow “indefinitely” as long as the sample remains in the superconducting state. Recent experiments on superconducting magnets operated with the terminals “superconductively shorted together” have shown that if the current did decay, the decay time would be something like 150,000 years corresponding to a resistivity of less than $10^{-22}$ ohm-cm, which is at least 16 orders of magnitude smaller than the resistivity of copper at room temperature.

3) Critical Magnetic Field: A superconductor, at a temperature below the critical temperature, will remain in the superconducting state provided that the sample is not exposed to a magnetic field above a “critical” value, characteristic of the particular superconductor, which depends on temperature, it is zero at (and above) the critical temperature and slowly increases as the temperature is lowered below the critical temperature.

4) Critical Current Density: A superconducting sample, at a temperature below the critical temperature, can carry a DC current without resistance up to some critical current density, above which the sample will revert to the normal (resistive) state. While the critical temperature and the critical magnetic field are characteristics of the material, the critical current density for a sample is very sensitive to the physical and metallurgical state of the sample.

5) Magnetic Flux Exclusion: When a superconductor is placed in a magnetic field, the magnetic field is excluded from the interior of the sample, except for a small surface region characterized by a “penetration depth”. This effect is called the “Meissner Effect” after one of the discoverers [8].

6) Magnetic Flux Quantization: If a magnetic field does penetrate into a superconductor, for example in the case of a loop of superconductor, the magnitude of the magnetic field surrounded by the superconductor will be quantized in units of $\hbar/2e$ where $\hbar$ is Planck’s constant and $e$ is the charge on the electron. This unit of magnetic flux is known as the “magnetic flux quantum”.

7) Josephson Junction: A Josephson junction [9] consists of two superconducting specimens separated by a barrier region which can be an insulator, a conductor or another superconductor where the “barrier” which controls the magnitude of the superconducting current flowing between the two superconductor “electrodes” depends on the dimensions and electrical properties of the “barrier” between the two electrodes. The very non-linear characteristic of a Josephson device can be used as a detector or mixer of radiation in the microwave, terahertz and infrared frequency regions of the spectrum, as a variable inductor in electrical circuits and as a very low power dissipation, very high speed switch in digital circuits. Furthermore, the Josephson junction is the basis for the currently accepted International Voltage Standard.

8) Superconducting Energy Gap: According to the BCS theory, the Cooper pairs are bound together with an energy $\Delta E$ given by the relationship

$$\Delta E = h\nu = 3.52k_BT_c$$

where $h$ is Plancks constant ($h = 6.6262 \times 10^{-34}$ Joule-sec), $\nu$ is the frequency, $k_B$ is Boltzmann constant ($k_B = 1.3806 \times 10^{-23}$ Joules/Kelvin) and $T_c$ is the superconducting transition temperature. The photon frequency corresponding to the energy gap of a superconductor with a $T_c = 1$ K is about 73 GHz. Thus the energy gap of most superconductors corresponds to photons in the terahertz or far infrared frequency regions of the spectrum.

9) Electrical Losses at Finite Frequencies: The resistance of a superconductor is “zero” only at DC. For frequencies, $f$, much smaller than that corresponding to the energy gap, the resistance of a superconductor is given by the BCS theory as:

$$R_{BCS} \approx \frac{(2\pi f)^2}{T} \exp(-1.76 \frac{T}{T_c}).$$

For frequencies much greater than that corresponding to the energy gap, the superconductor behaves like a normal conductor with the customary square root of the frequency dependence for the resistivity. For more detailed information about these properties of the superconducting state, the reader should consult some of the standard references given at the end of this manuscript [10].

IV. APPLICATIONS OF SUPERCONDUCTIVITY AT HIGH FREQUENCY FIELDS

In exploiting the unique properties of superconductivity for high frequency applications, the properties most commonly used are the (near) “zero” resistance of superconductors at finite frequencies and the nonlinear properties of the Josephson Effect. Other properties employed include magnetic flux quantization and the (abrupt) transition from the normal to the superconducting state at “zero” frequency. The critical current density is another important parameter as it is a measure of the maximum power that the device can transport.
A. Band Pass and Band Reject Filters

The most common application of superconductivity at high frequencies is the construction of bandpass and band reject filters. In general the Q-value of the filter structures depend on the volume of the devices with higher Q-values requiring a larger volume: 3-dimensional resonators tend to have high Q-value and large volume while thin film resonators are much smaller in size with noticeably smaller Q-values. Thus, since the resistive losses for a superconductor at finite frequencies are much less than that of a normal metal device of the same geometry, filters and resonators are an attractive application opportunity for superconductors.

One of the earliest reported research on thin film superconductor microwave filter structures was in 1971 when DiNardo et. al. [11] reported on thin lead ring resonators and half wave length resonators operating at 14 GHz which exhibited unloaded Q-values of about 200,000 at 4 K and about 500,000 at 1.8 K. These values of Q are extremely difficult to realize using normal conducting materials, even for structures with very large physical dimensions.

Despite the very impressive Q-values obtained for these devices, little subsequent work on thin film microwave resonant devices operating at 4 K were reported until recently, when projects have started using high-Q, low loss microwave resonators in the readout circuits of Transition Edge Sensors (TES) devices and for Quantum Computing applications. These specific applications will be addressed by other papers in this Special Session.

Although there was only little interest in thin film superconductor resonant circuits at 4 K, there has been a strong interest in 3-dimensional resonant cavities by the high energy physics community. Superconducting 3-dimensional radio frequency (RF) and microwave frequency resonators are commonly used in High Energy particle accelerators, such as the Large Hadron Collider (LHC) operating at CERN in Europe, to accelerate the particles. The cavity geometry that is used has a path where there is a very high electric field gradient along which the beam can be passed to give the particles an energy increase as it circulated around the accelerator. Since these cavities are operated at very high power, a very high Q implementation is essential to minimize the thermal heat load on the refrigeration system used to provide the required cryogenic environment for these cavities. Superconductivity is the only known technology that can provide the very high Q-values required for this application!

Fig. 4 is a picture of a 9 cell niobium cavity operating at 1.3 GHz designed for the International Linear Collider (ILC) which is proposed as the next generation of high energy particle accelerators [12]. The unit is about 1 meter in length and when operated at 1.8 K exhibits a Q-value in excess of $10^{11}$!
B. Josephson Junction Devices

A Josephson Junction is a device consisting of two superconducting electrode separated by a “barrier” which can be an insulator, a normal metal, a superconductor with a lower transition temperature than the electrodes, or, even, a dimensional constriction in the direction of current flow. The current, \( i \), flowing through such a devices is given by the Josephson theory to be

\[
\begin{align*}
    i &= i_0 \sin \left( 2\pi \frac{\phi}{\phi_0} \right) \\
    \text{(3)}
\end{align*}
\]

where \( i_0 \) is the maximum value of the supercurrent that can flow through the devices before a voltage appears across the structure, \( \phi_0 \) is the magnetic flux quantum \((2.07 \times 10^{-15} \text{ Webers})\) and \( \phi \) is the magnetic flux threading the barrier region. Since magnetic flux is given by

\[
\phi = \int V \, dt, \quad \text{(4)}
\]

it is obvious that the I vs. V characteristic of a Josephson junction is extremely non-linear. This non-linear behavior has been used to fabricate very sensitive mixers and detectors of microwave and terahertz radiation and, until the recent development of cryogenically cooled semiconductor InP FET devices; superconductor SIS devices were the preferred technology for radio astronomy applications in the microwave frequency regime. The non-linear I-V characteristics have also been employed as a non-linear inductor for the sensitive element in parametric amplifiers with noise temperatures well below 1 K for 4 K operation. Although it is not quite so obvious, the very non-linear response of the Josephson device to radiation has been used to construct the international accepted Voltage Standard which has demonstrated a precision of better than 1 parts per billion.

When a current less than the critical current \( i_0 \), is flowing through a Josephson device in the superconducting state, if the impressed current is increased above \( i_0 \), or if a magnetic field is applied to the devices which will suppress the critical current the device will switch into the normal (resistive) state at a time corresponding to a frequency greater than 775 GHz where the power dissipated by the device (in the normal state) is much less than a microwatt! This fast switching speed for the Josephson device has lead to a family of very high-speed digital and mixed signal devices. Analog-to-digital converters operating with clock frequencies in the 40 GHz range (and capable of even higher clock speeds) have been demonstrated to date which can digitize signals well into the microwave frequency range. These circuits employ the movement of magnetic flux quanta around the circuit and therefore, this technology inherently has extremely high precision as the “unit of information” is quantized [13]. A paper in this Special Session will address the use of Josephson digital devices to produce mixed signal circuits operating at clock frequencies up to and greater than 50 GHz. If these superconductor mixed signal circuits can be built with sufficiently high sensitivities, they can be placed directly behind the antenna and the signal could be immediately digitized without the use of analog pre-amplifiers which can introduce noise and distortion into the signal. [14]

V. Summary

The 100th anniversary of the discovery of superconductivity is being observed in 2011 and a Historic Session has been organized for IMS 2011. There are many very unique properties of superconductivity that can be used to make electrical and electronic devices with properties and characteristics that are, in many cases, impossible to achieve using non-superconducting technologies. In this paper, a brief overview of the history of superconductivity was presented along with a brief review of the properties of superconductivity that can be used in high frequency devices and circuits. Some of the earlier attempts to use superconductivity in microwave applications were outlined. In the following paper, additional applications of microwave superconductivity will be described, especially those employing high temperature superconductors which were discovered in 1986. Other papers in this Special Session, will describe some additional research thrusts in microwave superconductivity.

REFERENCES