III-2. MICROWAVE APPLICATIONS OF SUPERCONDUCTIVITY

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Introduction. For many years after the discovery of superconductivity in 1911, the phenomenon remained largely a laboratory curiosity. For over 40 years physicists worked with only moderate success to gain a theoretical understanding of superconductivity. In recent years, however, the situation has changed rapidly. An adequate theory has now been developed (the BCS theory[1]), and superconductivity has become a useful tool in many fields of pure and applied research. As an outstanding example, superconducting magnets are now available commercially which can generate dc fields up to 100 kilogauss.

Surface Resistance of a Superconductor. Following the development of high frequency sources and techniques during World War II, the RF properties of superconductors have been extensively investigated. Although a dc current can flow in a superconductor without loss, this is not true for ac currents. The two-fluid model provides a simple physical explanation for the ac loss. According to this model, both normal and superconducting electrons are present in a superconductor below the transition temperature. The superconducting electrons can carry a steady current without loss. However, the superconducting electrons have inertia, and an electric field is necessary to produce the acceleration associated with an alternating flow of current. This electric field also acts on the normal electrons, and a flow of normal current with power loss results. A simple calculation shows that the surface resistance is proportional to the square of the frequency for frequencies below the microwave range. In the two-fluid model the number of normal electrons, and hence the surface resistance, decreases rapidly with decreasing temperature. At absolute zero there are no normal electrons remaining and hence in theory the surface resistance should vanish.

The frequency and temperature dependence of the superconducting surface resistance R has been obtained more quantitatively from a calculation[2] based on the BCS theory. For frequencies below about 10 GHz and in the temperature range of interest, the theoretical surface resistance can be written as:

$$R \propto \frac{1}{Q} \propto \frac{\omega^2}{T} e^{-\epsilon/kT} \qquad (1)$$

where 2ϵ is the gap in the energy spectrum of the superconductor and is the angular frequency. Note that R vanishes exponentially as the absolute temperature T approaches zero, while the Q of a resonant cavity, which is equal to a geometry-dependent constant divided by R, will approach infinity.

The fact of superconductivity is also shown by the BCS theory to be dependent on the existence of an energy gap. As the frequency is increased, the point will eventually be reached where the microwave photons will have sufficient energy to cause excitation across the gap. Thus when $h\nu > 2\epsilon$ where ν is the frequency and h is Planck's constant, the loss at a given temperature will increase sharply, and further, a finite resistance will now be present even at $T = 0^\circ$ K. For lead this transition occurs at about 500 GHz. The behavior of the superconducting surface resistivity as a function of temperature and frequency is illustrated qualitatively in Fig. 1.

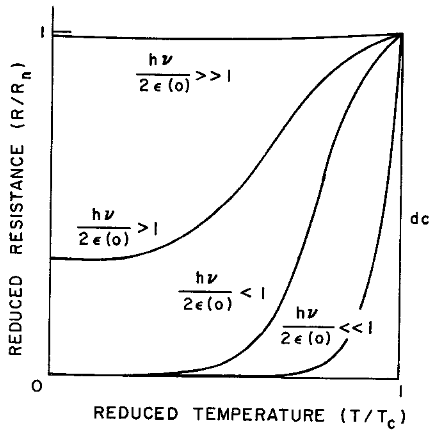

Figure 1. Qualitative frequency and temperature dependence of the surface resistance of a superconductor. Here R_n is the surface resistance just above the transition temperature T_c.

In practice the measured surface resistance does not vanish as T approaches zero, even at low frequencies. Instead it approaches a limiting value termed the residual resistance. The residual loss depends on such factors as impurities and strains in the surface, surface roughness, and trapped magnetic flux. The details of the techniques used in preparing and handling the surface will determine how low in practice the residual resistance can be made.

At Stanford we have measured[3,4] the surface resistance of tin, lead, and niobium surfaces using resonant cavities at S-band and X-band. In a TE_{011}-mode cylindrical cavity with a surface of electroplated lead operating at 2856 MHz, we have obtained an unloaded Q of 5×10^9 at a temperature of 1.8° K. In addition rf magnetic fields on the order of 300 gauss and rf electric fields of 1.3×10^5 volts/cm have been sustained with little degradation in cavity Q. These numbers are sufficiently attractive that it is now possible to consider the application of superconductivity to a variety of microwave devices.

The theoretical increase in Q of a lead-plated superconducting cavity over the Q of an identical copper cavity at room temperature is given in Table I for three values of absolute temperature. Our experience has been that even a surface of modest quality will give improvement factors close to those shown at 4.2° K. Our best electroplated surfaces have come within a factor of two of the values shown for 2.0° K. at S-band and X-band. However, even a small residual loss is important at 1.5° K, and further improvements in surface quality must be made before the values shown in Table I for this temperature can be realized. The relative values of the theoretical and measured Q as a function of temperature for a cavity with good electroplated surface is shown in Fig. 2. The effect at low temperatures of the residual resistance is apparent.

TABLE I. Theoretical Q Improvement Factors For Lead-Plated Cavities

T °K	10,000 MHz	3,000 MHz	1,000 MHz	300 MHz
4.2	6×10^2	3×10^3	1.5×10^4	1×10^5
2.0	2×10^4	1×10^5	5×10^5	3×10^6
1.5	2×10^5	1×10^6	5×10^6	3×10^7

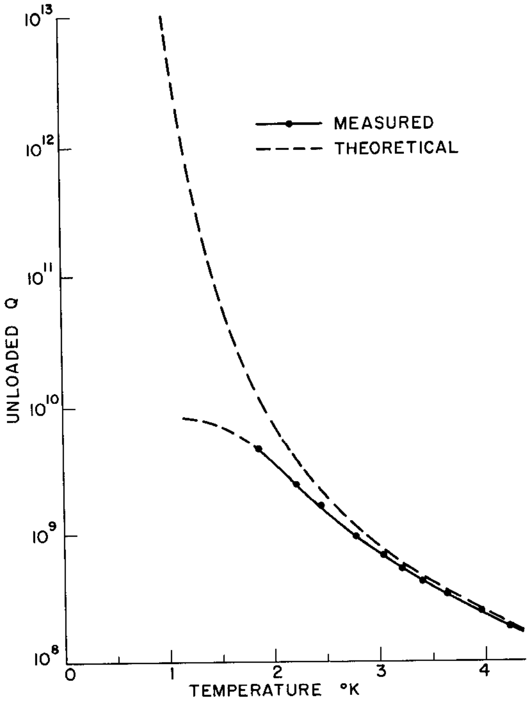

Figure 2. Theoretical and measured Q as a function of temperature for a TE_{011}-mode cavity with an electroplated lead surface at 2856 MHz.

Application to Particle Accelerators. The measurements at Stanford on superconducting cavities were initiated in order to study the feasibility of superconducting linear electron accelerators. Because conventional electron linacs require a power dissipation on the order of one megawatt per foot to produce an energy gradient of a few MeV per foot, these machines are necessarily pulsed at low duty cycles, typically in the range of 10^{-4} to 10^{-3}. Low duty cycle imposes a severe limitation on the type of nuclear and particle physics experiments that can be performed using such machines. By making the rf structure superconducting, energy gradients of several MeV per foot can be produced with a power dissipation of only a few watts per foot, and consequently the rf power and the beam can be run continuously. Because of the poor efficiency of low temperature refrigeration, a refrigerator input power of a few kilowatts per foot is necessary. The design principles for superconducting electron linacs have been given elsewhere[5]. Table II shows the parameters for two possible accelerators of this type--

TABLE II. Superconducting Linac Designs

Operating Frequency	1 GHz
Operating Temperature	1.8° K
Unloaded Q	1×10^{10}
Shunt Impedance	1.2×10^{11} ohms/cm
Mode	π

Length	500 ft.	10,000 ft.
Energy (cw)	1.5 GeV	20 GeV
Beam Current (cw)	330 ua.	250 ua.
Beam Power (cw)	500 kw.	5 Mw.
Energy (pulsed)	3.0 GeV	60 GeV
Duty Cycle (pulsed)	25%	11%
Beam Current (pulsed)	80 ua.	20 ua.
Power Dissipated at 1.8° K	1.2 kw.	11 kw.
Est, Power Input to Refrig.	2 Mw.	18 Mw.
Est. Refrigerator Cost	$\$1.5 \times 10^6$	$\$10 \times 10^6$
No. of Klystrons (20 kw av, 40 kw pulsed)	25	250
Power Input to Klystrons	1.2 Mw.	12 Mw.
Coupling Coefficient (cw)	400	450
Loaded Q (cw)	2.5×10^7	2.2×10^7
Filling Time (cw)	4 ms.	9 ms.
Coupling Coefficient (pulsed)	200	100
Loaded Q (pulsed)	5×10^7	1×10^8
Filling Time (pulsed)	8 ms.	16 ms.

* Limited to 10 MeV per foot due to critical magnetic field.

a superconducting version of the present Stanford Mark III accelerator and a superconducting SLAC.

Superconductivity can also be applied to other types of particle accelerators. Several laboratories have investigated the possibility of superconducting proton linacs. As in the case of the electron linac, the principal motivation is to gain duty cycle. The frequencies of interest for such accelerators lie in the range from 200 to 800 MHz. Superconducting rf particle separators have also been proposed[5,6]. An rf separator gives a transverse momentum kick to the particles rather than an acceleration in the direction of motion. Existing rf separators operate at S-band. As in the case of the linac, very high peak powers are required to produce the fields in conventional separators, and consequently they must be operated at low duty cycles. Superconducting rf separators would find an immediate use in connection with existing electron and proton synchrotrons. These machines have a high duty cycle of a few percent and higher. Superconducting cavities have also been proposed as a means of eventually raising the energy of the Cornell electron synchrotron now under construction from the present design value of 10 GeV to 15 GeV. The rf cavities for this accelerator will operate at 714 MHz.[5]

As a final application in the field of particle accelerators, superconductivity can be applied to the rf system of a racetrack microtron. Such a machine, operating at 1 GHz, could deliver a 100-microampere beam of electrons at 400 MeV with a duty cycle of 100%. The advantage of the microtron over the linac is that the beam is recirculated through the rf cavity on the order of twenty times, making it possible to reach a considerably higher energy for a given power dissipation. The resulting machine is therefore more compact than a linac of equivalent energy, and has in addition a higher inherent energy resolution. Unfortunately, the cost of the magnet increases rapidly with increasing energy, and microtrons probably are not economically feasible above about 1 GeV.

Other Applications. High Q superconducting cavities have an obvious application to highly stable frequency sources. A TE_{111}-mode cylindrical cavity operating at 3160 MHz has been used[8] to stabilize a TWT oscillator. A superconducting monotron oscillator has also been proposed[9]. It is difficult to predict the ultimate stability that can be achieved by the use of superconducting cavities. However, a TE_{011}-mode cavity operating at 1 GHz and 1.8° K has a theoretical Q of about 10^{11}. It is reasonable to consider stabilizing an oscillator to 0.1% of the cavity bandwidth, giving a stability of 10^{-14} in this case. Such a cavity would have a filling time of 20 seconds. If the excitation is removed, the cavity would act during the decay time as a power source with a relative bandwidth of 1/Q. Still higher stabilities and longer decay times are possible in principle at lower temperatures or longer wavelengths.

Superconducting cavities are useful tools in basic physics research. They can be employed directly to measure the penetration depth, energy gap, and rf critical magnetic field for superconducting surfaces. The measurements can then be compared with the predictions of the BCS theory. Superconducting cavities can be used indirectly in basic research in a variety of ways. For example, changes in the level of liquid helium in such a cavity can be measured very accurately by observing changes in the resonant frequency. Similarly, a superconducting cavity can be used to measure very small changes in length or position. A movement as small as 10^{-10} cm can be detected in the position of the end plate of a TE_{011}-mode mode cavity operating at 3 GHz and 1.8^{o} K.

Resonant cavities have been used to measure the velocity of light. However, previous measurements were limited in precision by uncertainties in the surface reactance of room-temperature cavities[10]. Use of a superconducting cavity would reduce this source of error by two orders of magnitude. Perhaps a precision measurement of the velocity of light using this method sould be reconsidered.

As a final application of superconductivity at microwave frequencies, we will consider effects based on the non-linear behavior of a superconductor[11]. These effects fall into two classes. First, the superconductor can switch into the normal state if the dc or rf magnetic field (or the sum of the two) at the surface is sufficiently high. Harmonic power generation as the result of switching has been observed by several investigators[11], both in a resonant cavity and in thin films placed across a waveguide. Secondly, the electrodynamics of a superconductor is non-linear even at low fields and currents under certain conditions. Frequency conversion, mixing, and parametric amplification have been seen[12] as the result of the non-linear reactance of thin superconducting tin films.

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