

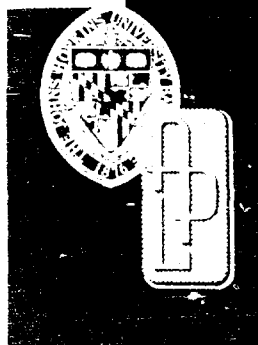
4

AD-A218 805

JHU/APL

TG 1377

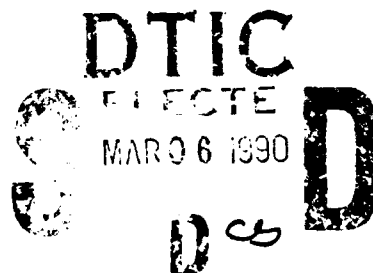
FEBRUARY 1990



Technical Memorandum

**APPLICATION OF HIGH-TEMPERATURE
SUPERCONDUCTING THIN-FILM DEVICES TO
ELECTRO-OPTICAL AND ELECTRONIC
WARFARE SYSTEMS**

B. G. BOONE



THE JOHNS HOPKINS UNIVERSITY ■ APPLIED PHYSICS LABORATORY

Johns Hopkins Road, Laurel, Maryland 20707

Operating under Contract N00039-89-C-5301 with the Department of the Navy

Approved for public release; distribution unlimited.

90 03 05 015

JHU/APL
TG 1377
FEBRUARY 1990

Technical Memorandum

**APPLICATION OF HIGH-TEMPERATURE
SUPERCONDUCTING THIN-FILM DEVICES TO
ELECTRO-OPTICAL AND ELECTRONIC
WARFARE SYSTEMS**

B. G. BOONE

THE JOHNS HOPKINS UNIVERSITY ■ APPLIED PHYSICS LABORATORY
Johns Hopkins Road, Laurel, Maryland 20707
Operating under Contract N00039-89-C-5301 with the Department of the Navy

Approved for public release; distribution unlimited.

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified			1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited	
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE				
4. PERFORMING ORGANIZATION NUMBER(S) JHU/APL TG 1377			5. MONITORING ORGANIZATION REPORT NUMBER(S) TG 1377	
6a. NAME OF PERFORMING ORGANIZATION The Johns Hopkins University Applied Physics Laboratory		6b. OFFICE SYMBOL (If Applicable) FIF	7a. NAME OF MONITORING ORGANIZATION NAVPRO/Laurel, Md.	
6c. ADDRESS (City, State, and ZIP Code) Johns Hopkins Road Laurel, MD 20707			7b. ADDRESS (City, State, and ZIP Code) Johns Hopkins Road Laurel, Maryland 20707	
8a. NAME OF FUNDING/SPONSORING ORGANIZATION SPAWAR		8b. OFFICE SYMBOL (If Applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N00039-89-C-5301	
8c. ADDRESS (City, State, and ZIP Code) Arlington, VA 22209			10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. PROJECT NO. TASK NO. WORK UNIT ACCESSION NO.	
11. TITLE (Include Security Classification) Application of High-Temperature Superconducting Thin-Film Devices to Electro-Optic and Electronic Warfare Systems				
12. PERSONAL AUTHOR(S) B. G. Boone				
13a. TYPE OF REPORT Technical Memorandum		13b. TIME COVERED FROM 5/88 TO 12/89	14. DATE OF REPORT (Year, Month, Day) 1990, February	15. PAGE COUNT 47
16. SUPPLEMENTARY NOTATION				
17. COSATI CODES FIELD GROUP SUB-GROUP			18. SUBJECT TERMS High-temperature superconductors Thin-film devices Electronic warfare Electro-optics Radiation detectors Passive microwave components	
19. ABSTRACT (Continue on reverse if necessary and identify by block number) <p>This report gives an assessment of the impact of high-temperature superconductivity on applications in electro-optical and electronic warfare. Prior art in low-temperature superconductivity provides many examples of potential applications. It is essential that the feasibility of developing and using specific high-temperature superconducting devices, such as radiation detectors and passive microwave components, be determined before significant systems investment occurs. Research and development activities at the Applied Physics Laboratory aimed at implementing such thin-film devices are underway.</p>				
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL NAVPRO Security Officer			22b. TELEPHONE (Include Area Code) (301) 953-5442	22c. OFFICE SYMBOL NAVPRO SE

ABSTRACT

This report gives an assessment of the impact of high-temperature superconductivity on applications in electro-optical and electronic warfare. Prior art in low-temperature superconductivity provides many examples of potential applications. It is essential that the feasibility of developing and using specific high-temperature superconducting devices, such as radiation detectors and passive microwave components, be determined before significant systems investment occurs. Research and development activities at The Johns Hopkins University Applied Physics Laboratory aimed at implementing such thin-film devices are underway.

Date	
APR 1978	<input checked="" type="checkbox"/>
1978	<input type="checkbox"/>
1978	<input type="checkbox"/>
By	
Distribution	
Availability Codes	
1978	1978
A-1	



EXECUTIVE SUMMARY

The application of high-temperature superconducting (HTSC) thin-film devices to electro-optical and electronic warfare systems is a likely near-term outcome of recent breakthroughs in the field of superconductivity. The following report addresses this topic from a systems level as well as at the component level. It emphasizes the use of HTSC materials, in particular applications of potential interest to the U.S. Navy, but the treatment of these applications is very general and not mission-specific. Greater emphasis is put on highlighting the technology and those superconducting properties important to particular devices that could be used in many different systems. For instance, surface resistance is a key parameter for making low-loss and high-quality HTSC microstrip delay lines and resonators, respectively. Such devices can be incorporated into high-frequency radar receivers and signal processors as well as other systems.

The introduction and background section of this report cites recent Navy guidance on superconductivity research and development. The basic properties of superconductors are reviewed, including zero resistance, the Meissner effect, flux quantization, and the Josephson effect. Then device-specific properties (e.g., the superconducting quantum interference device [SQUID] response) are explained. A technology survey and assessment gives an overview of prior art in low-temperature superconductivity, discusses actual and potential applications, and provides a summary of recent HTSC research and development up to the end of 1988. The requirements placed on superconducting devices by potential applications are then examined, and projections are given for those devices when made with HTSC materials. Candidate subsystems for HTSC insertion as well as implementation and integration issues (e.g., cryogenic cooling, semiconductor/superconductor interfacing, and fabrication process compatibility) are considered. Finally, some general comments are made on the future of superconducting devices and applications. Each major section of this report stands alone and thus can be read independently and according to the interests of the reader.

The purpose of this report is to give a Fleet Systems perspective to the above-mentioned Applied Physics Laboratory projects. It should also help both APL management and current or future Navy sponsors of APL work to understand the connections between their future systems needs and the HTSC technology. By seeing the potential for application of HTSC devices to Navy needs as described herein and by recognizing the interest the Navy has at the highest level in administering superconductivity research and development, it is hoped that APL management and potential sponsors can acknowledge the commitment needed to bring the promise of HTSC technology to reality.

CONTENTS

List of Figures.....	7
List of Tables.....	9
1.0 Introduction and Background.....	11
2.0 Basic Properties of Superconductors.....	13
3.0 Technology Survey and Assessment.....	18
3.1 Overview of Prior Art.....	18
3.2 Potential Applications.....	23
3.3 Current Research and Development.....	27
4.0 Requirements for Technology Development.....	31
4.1 System Application Requirements.....	31
4.2 Projected Performance Gains.....	34
4.3 Candidate Subsystems for HTSC Insertion.....	35
4.4 Implementation and Integration Issues.....	36
5.0 Conclusions and Future Considerations.....	40
References	41
Glossary	45

LIST OF FIGURES

1. Resistance versus temperature for YBCO superconductor ($T_c = 90$ K).....	13
2. Process of expelling a static magnetic field (B-field) in a superconductor as temperature is brought below T_c	13
3. Parameter space for the superconductor showing surface between normal and superconducting states and associated critical parameters T_c , I_c , and H_c	13
4. Superconducting ring showing condition of trapped flux and persistent current below T_c	14
5. Two common examples of Josephson junctions: (a) microbridge and (b) tunnel junction. Corresponding I - V curves: (c) microbridge I - V curve and (d) hysteretic tunnel junction curve.....	15
6. Equivalent circuit model of the intrinsic response of the superconducting weak link.....	15
7. Categories of applications and examples of corresponding superconducting devices.....	18
8. Magnetic flux scale; schematic diagrams of DC and RF SQUID's; and corresponding response curves.....	19
9. Two examples of simple nondispersive microstrip resonators that can be made using HTSC materials.....	20
10. Example of superconducting computer memory circuit that	

could use microstrip interconnects (multiple-flux-quanta memory loop).....	20
11. Basic design layout of a superconducting dispersive (chirp) delay line.....	20
12. Simple slow-wave meanderline device.....	21
13. Josephson junction circuit and superconducting integrated circuit.....	22
14. Optically induced waveform sampling using coplanar transmission lines.....	22
15. HTSC electrodes can be used as gates for GaAs MESFET amplifiers.....	22
16. Speed versus power dissipated per gate for various semiconductor and superconductor technologies.....	23
17. Low-temperature millimeter-wave receiver using superconducting SIS mixer and HEMT amplifier.....	23
18. Comparison of wavelength coverage of HTSC and semiconducting detector technologies.....	26
19. Comparison of the sensitivity of superconducting detectors at various temperatures against an ideal room-temperature semiconducting photoconductor.....	26
20. Plot of calculated surface resistance versus frequency for 1-2-3 ceramic (YBCO) superconductors and recent measurements and comparison to calculations for copper at various temperatures.....	28
21. Architecture for a generic electronic warfare system.....	32
22. Basic elements of a generic focal plane array.....	33
23. Spectral range of typical targets and atmospheric transmission function over visible and infrared bands.....	33
24. Summary of prior art in bolometers and comparison to typical application requirements.....	33
25. Quasi-optical impedance matching "vee" antenna for a possible HTSC bolometer.....	35
26. Some possible HTSC microstripline components.....	36
27. Integrated circuit microstrip oscillator using feedback coupling, consisting of an HTSC ring resonator, HTSC interconnects, hybrid phase shifter, and GaAs amplifier on a common chip.....	36
28. Typical circuit configuration and mesoscopic detail of a grain-boundary array-type HTSC microbridge.....	37
29. Microminiature refrigerator using capillary Joule-Thompson cooler etched in sapphire substrate.....	38
30. Small-scale Joule-Thompson cooler for missile-guidance applications.....	38
31. Closed-cycle (Stirling) cryocooler for IR FPA's.....	39
32. Typical monopulse radar block diagram showing possible HTSC device insertion points.....	39
33. Typical ESM block diagram showing possible HTSC device insertion points.....	39

LIST OF TABLES

1. Fundamental superconductor parameters.....	16
2. NCS assessment of high-frequency applications of HTSC materials to particular electronic warfare missions.....	24
3. Inferences from NCS HF assessment.....	25
4. Rating of generic categories from NCS HF assessment.....	25
5. NCS assessment of IR FPA requirements.....	26
6. Recent research results in HTSC resonators.....	28
7. Recent results for flux noise in RF and DC SQUID's.....	30

1.0 INTRODUCTION AND BACKGROUND

An unprecedented opportunity exists to exploit new high-temperature superconducting (HTSC) materials in micro electronic circuits. The onset of superconductivity in the higher transition temperature (T_c) phase of the bismuth-strontium-calcium-copper-oxide (BSCCO) system occurs at around 105 K, thus allowing the use of cheap and easily managed liquid nitrogen (77 K) based cryogenics for effective reduced temperatures (T/T_c) of ~ 0.70 . Alternatively, the lower T_c phase of BSCCO could be used in a resistive transition bolometer near 77 K. The application of such devices to Navy systems is being addressed at The Johns Hopkins University Applied Physics Laboratory. Specific components, however, should be developed and demonstrated in general technology areas for potential application to Navy problems. Among the many possible uses to be considered, APL is investigating simple, passive thin-film devices such as detectors of electromagnetic radiation and monolithic microwave integrated circuit (MIMIC) components.

New HTSC devices are expected to exhibit excellent performance as radiation detectors in two related ways. First, they should operate with good spectral response at extremely high frequencies reaching into the far-infrared band. Second, broadband electrical response can be achieved at extremely high frequencies before intrinsic response-time limitations occur. Both features depend on the very high superconducting energy gap found in HTSC materials (≤ 50 mV). Sensitivity (as measured by root-mean-square noise) should also be good for devices made with these materials but will be temperature-limited compared to low- T_c superconducting (LTSC) devices. The HTSC materials, however, exhibit good resistance to ionizing radiation.

Microelectronic thin-film devices fabricated from HTSC materials must exhibit stable mechanical, electrical, and thermal properties. The new BSCCO material is more stable and therefore easier to work with than yttrium-barium-copper-oxide (YBCO) material. The BSCCO material has been fabricated into simple thin-film devices at APL, but the T_c 's are indicative of a two-phase material with a predominant lower T_c phase. Fabrication procedures are being developed to deposit and pattern thin films of BSCCO on technologically useful substrates for practical device applications. A major milestone will be to achieve a T_c approaching 105 K. The use of YBCO thin films in the same devices is also being pursued.

The Navy's superconductivity community supports efforts to develop the new HTSC materials in useful devices. The Chief of Naval Research has indicated that U.S. industries (including systems laboratories such as APL) should identify application needs and areas for partici-

pation with the Navy R&D laboratories.¹ The Office of Naval Technology has indicated that, "IR&D can help focus future Navy 6.2 efforts."²

Another key focus is HTSC MIMIC device insertion, with potential uses in radar, communications, surveillance, guidance, and electronic warfare. Certain critical components are used for signal processing in these applications, for example, resonators, delay lines, and high-speed interconnects. The performance of such devices could be significantly enhanced by using new HTSC materials.

Microstrip resonators with extremely high quality (Q) values on the order of 10^5 or higher can be fabricated and integrated into highly selective oscillators for spread spectrum radar³ and extremely stable frequency standards. Conventional superconductors need liquid helium cryogenic equipment,⁴ which is expensive and cumbersome to work with.

Microstrip delay lines can also be fabricated and inserted into circuits for use as signal storage and dispersive elements. Under the action of modulating signals or by using patterned films, such delay lines can perform variable or fixed delays appropriate for wideband receivers⁵ or narrow-band oscillators.⁶ Microstripline interconnects in MIMIC and very-large-scale integrated circuits for high-speed communications and computing is another area of application. These interconnects must be shortened to match the speed increases already being realized in the logic gates of such systems. Superconducting striplines⁷ would make this possible, with a subsequent

¹J. R. Wilson, "U.S. Navy Plans and Programs for Superconducting R&D," Proc. of the Conference on Superconductivity R&D in the U.S. Navy, NSWC, White Oak, Md. (9-10 Feb 1988).

²J. R. Cauffman, "Office of Naval Technology (ONT) Exploratory Development Program (6.2) in Superconductivity," Proc. of the Conference on Superconductivity R&D in the U.S. Navy, NSWC, White Oak, Md. (9-10 Feb 1988).

³J. J. Suter and A. G. Bates, "Ultra-Stable Time and Frequency Device for Tactical Aircraft Radar," JHU/APL SDO 8446 (Apr 1987).

⁴A. L. DiNardo, J. G. Smith, and F. R. Adams, "Superconducting Microstrip High- Q Microwave Resonators," *J. Appl. Phys.* **42**, 186 (1971).

⁵R. S. Withers, A. C. Anderson, J. B. Green, and S. A. Reible, "Superconductive Delay-Line Technology and Applications," *IEEE Trans. Magn.* **21**, 186 (1985).

⁶S. R. Stein and J. P. Turneare, "Superconducting Resonators: High Stability Oscillators and Applications to Fundamental Physics and Metrology," in *Future Trends in Superconductive Electronics*, AIP Conf. Proc. #44, B. S. Deaver, Jr., C. M. Falco, J. H. Harris, and S. A. Wolf, eds., pp. 192-213 (1978).

⁷R. L. Kautz, "Miniaturization of Normal-State and Superconducting Striplines," *J. Res. Nat. Bur. Stand.* **84**, 247 (1979).

reduction in the overall scale of the chips by 2 to 3 orders of magnitude. Superconducting interconnects should also help improve the performance of discrete active components. For instance, the noise figure of MESFET (metal semiconductor field-effect transistor) amplifiers could be reduced from a 2- to less than 1-dB final noise figure using superconducting interconnects.⁸

Conventional LTSC materials may be replaced with new HTSC materials and still yield significant improvements over normal metal-based technology. Key concerns in developing the new HTSC materials are the effect of stoichiometry on the transition temperature and the effect of surface quality on the surface resistance. These

parameters will influence the performance gains expected from using HTSC materials in place of normal metals.

The Naval Consortium for Superconductivity (NCS) has made several recommendations in various application areas. In particular, the panel on high-frequency applications endorses investigations of radio frequency (RF) devices for antennas, detectors, and oscillators.⁹ Overall system performance gains are expected if efficient cryogenics can be developed. In addition, the NCS panel on infrared sensor systems endorses investigation of applications in focal plane arrays (FPA's) and similar detection devices.¹⁰ Details of the NCS assessment will be described in section 3.2.

⁸J. L. Abita, "Superconductive Electrode Semiconductor Components," JHU/APL TEO-87-072 (20 Apr 1987).

⁹R. J. Dinger, "NCS Panel on High Frequency Applications," Proc. of the Conference on Superconductivity R&D in the U.S. Navy, NSWC, White Oak, Md. (9-10 Feb 1988).

¹⁰M. Nisenoff, "Naval Consortium on Superconductivity, Panel on Infrared Sensor Systems," Proc. of the Conference on Superconductivity R&D in the U.S. Navy, NSWC, White Oak, Md. (9-10 Feb 1988).

2.0 BASIC PROPERTIES OF SUPERCONDUCTORS

The two fundamental properties of superconductors are the loss of all resistance to the flow of low-frequency electric current and the complete expulsion of static magnetic fields. Both phenomena occur below the so-called transition temperature (T_c) in certain metals and compounds, including the new high- T_c ceramic oxides. The loss of resistance is illustrated in Fig. 1,¹¹ and the process of expelling a magnetic field is shown in Fig. 2. This latter property of superconductors, namely diamagnetism, is also known as the Meissner effect.¹² Above a certain critical magnetic field, H_c , the superconductor is driven into the normal state.

The superconducting state of a particular material can be described parametrically as falling within the envelope defined by three parameters: temperature, current, and magnetic field. If any one parameter exceeds a critical val-

ue (T_c , I_c , and H_c , respectively), the superconducting state will be destroyed, as illustrated in Fig. 3. A small-scale superconducting device could operate near T_c (point A) because it may only require small currents and magnetic fields, but a large-scale superconducting device generally requires large currents and fields and must therefore operate at temperatures well below T_c (point B). (This distinction, however, is not always clearly met in practice.)

The properties of zero resistance and diamagnetism are manifestations of the long-range order of the superconducting state below T_c . This long-range order is a macroscopic quantum phenomenon characterized mathematically by a wave function, which describes the population

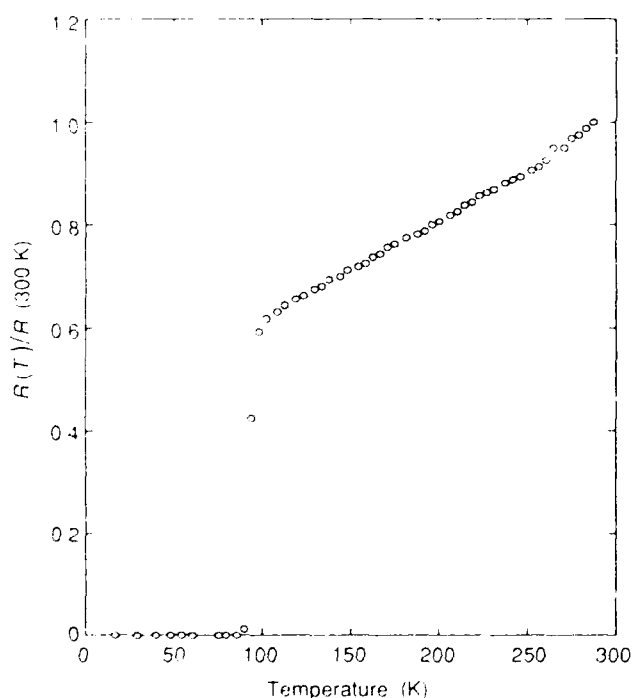


Figure 1 Resistance (R) versus temperature for YBCO superconductor ($T_c = 90\text{ K}$).

K. Moorjani, E. J. Adrian, B. F. Kim, J. Bohandy, I. E. Phillips, W. J. Green, E. Agostinelli, and B. G. Boone, "High Temperature Superconducting Thin Films," *Johns Hopkins APL Tech. Dig.* **9**, 174 (1988).

W. Meissner and R. Ochsenfeld, "Ein Neuer Effekt bei Eintritt der Supraleitfähigkeit," *Naturwiss.* **21**, 787 (1933).

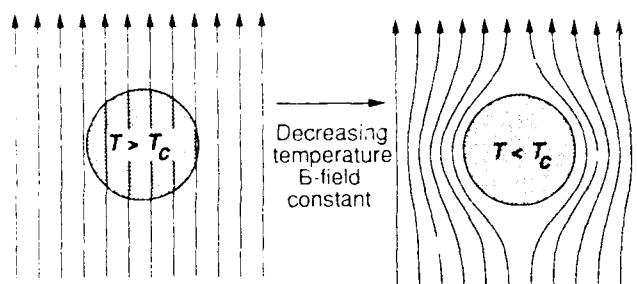


Figure 2 Process of expelling a static magnetic field (B-field) in a superconductor as temperature is brought below T_c .

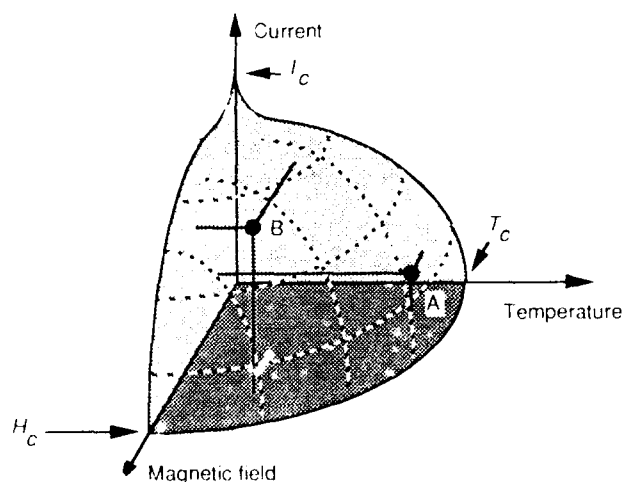


Figure 3 Parameter space for the superconductor showing boundary between normal and superconducting states and associated critical parameters T_c , I_c , and H_c .

of paired electrons that constitute the supercurrent carriers in a superconductor. The wave function is denoted by $\Psi(x, y, z, t)$ and is expressed as a complex quantity

$$\Psi = |\Psi| \exp(j\phi), \quad (1)$$

where the modulus $|\Psi|$ is commonly called the superconducting order parameter, and ϕ is the phase. $|\Psi|^2$ is equated with the number density, n_p , of paired electrons. The quantum theory that accurately describes the superconducting state is the Bardeen-Cooper-Schrieffer (BCS) theory, named after its originators.¹³

The electrons in a normal metal can be regarded as free to move within the crystal lattice, but they frequently collide with the lattice, creating a loss mechanism that yields a non-zero resistance at any temperature. In a superconductor, electrons of opposite momentum and spin near the so-called Fermi energy form bound pairs, which exhibit no loss under direct-current conduction. Their binding energy, Δ , is also the energy that separates the paired electron and unpaired electron populations (sometimes called quasiparticles) from each other in the conduction band.

The basic property of diamagnetism also leads to an important property of superconductors when constructed in the form of a ring. As a result of a transition to a superconducting state below T_c in the presence of a magnetic field, a superconducting ring will trap flux within the ring. The trapped flux induces a circulating current that persists indefinitely because of zero resistance (see Fig. 4). Quantum mechanics says that the phase of the macroscopic wave function must change by $2\pi n$ in going once around the ring. Combined with an expression for the supercurrent that includes a gradient of the phase, as well as the magnetic vector potential, the $2\pi n$ phase change results in quantization of the magnetic flux within the ring. The so-called flux quantum is given by

$$\Phi_0 = h/2e = 2 \times 10^{-7} \text{ Tm}^2, \quad (2)$$

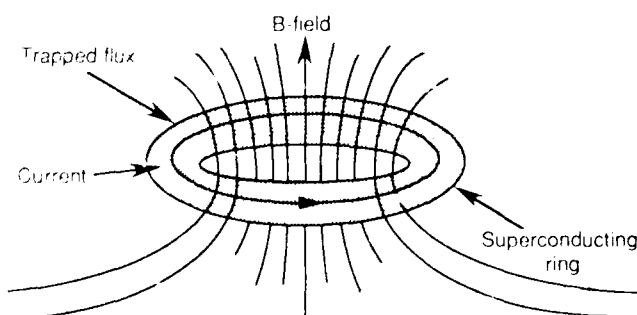


Figure 4 Superconducting ring showing condition of trapped flux and persistent current below T_c .

J. Bardeen, L. N. Cooper, and J. R. Schrieffer, "Theory of Superconductivity," *Phys. Rev.* **108**, 1175 (1957).

which is a very small flux quantity (h = Planck's constant, e = the electron charge). This effect was discovered experimentally by Deaver and Fairbank¹⁴ and Doll and Nabauer,¹⁵ and along with the Josephson effect, led to one of the few viable commercial applications of superconductivity in the form of super-sensitive magnetometers based on the superconducting quantum interference device (SQUID).

In addition to these basic properties of superconductors there is a fundamental effect predicted by Josephson¹⁶ and first measured by Anderson and Rowell,¹⁷ known as the Josephson effect, which is observed in the junction between two superconductors. A Josephson junction is a region between two pieces of superconductor where the superconducting state is weakened. This can be achieved by establishing a thin tunneling barrier or narrow connection (or contact) between the two superconductors. When the current (I) through the junction is increased from zero, Cooper pairs (paired electrons) tunnel quantum-mechanically through the barrier or connection, which establishes a phase difference ($\Delta\phi$) between the phases of the superconducting state on each side. The resulting current is given by

$$I = I_c \sin \Delta\phi, \quad (3)$$

where I_c is the critical current. This is the so-called DC Josephson effect. When the current through the junction exceeds I_c the phase difference evolves in time according to the relation

$$d\Delta\phi/dt = 4\pi eV/h, \quad (4)$$

where V is the voltage across the junction.

Equation 4 expresses the essence of the AC Josephson effect, and can be used to show that the Josephson junction is a voltage-controlled oscillator. The varied applications of Josephson junctions stem from the basic DC and AC Josephson effects just described as well as from suitable electronic circuits in which Josephson junctions reside. Josephson junctions can be used as sensitive detectors of millimeter waves as well as low-frequency magnetic fields. They have also been used as oscillators,

¹⁴B. S. Deaver, Jr., and W. M. Fairbank, "Experimental Evidence for Quantized Flux in Superconducting Cylinders," *Phys. Rev. Lett.* **7**, 43 (1961).

¹⁵R. Doll and M. Nabauer, "Experimental Proof of Magnetic Flux Quantization in a Superconducting Ring," *Phys. Rev. Lett.* **7**, 51 (1961).

¹⁶B. D. Josephson, "Possible New Effects in Superconductive Tunneling," *Phys. Lett.* **1**, 251 (1962).

¹⁷P. W. Anderson and J. M. Rowell, "Probable Observation of the Josephson Superconducting Tunneling Effect," *Phys. Rev. Lett.* **10**, 230 (1963).

parametric amplifiers, and digital logic switches (to name only a few).

The simplest examples of Josephson junctions are illustrated in Figs. 5(a) and 5(b), a microbridge junction and a tunnel junction (also known as a superconductor-insulator-superconductor [SIS] junction), respectively. A description of the fundamentals and types of Josephson junctions is given by Tinkham¹⁸ and will not be elaborated on here. The corresponding I - V curves for these two types of Josephson junction are shown in Figs. 5(c) and 5(d). Notice that the tunnel junction is hysteretic, having a forward branch that switches dramatically when the current reaches a value on the order of the critical current and a sharply varying return branch that occurs at a voltage equal to twice the gap voltage. The hysteresis is a function of the parasitic capacitance in the tunnel junction, making it useful in latching logic for computer circuits. The excess supercurrent and the ohmic line of the microbridge weak link can be modeled as a resistively shunted junction. These so-called equivalent circuit

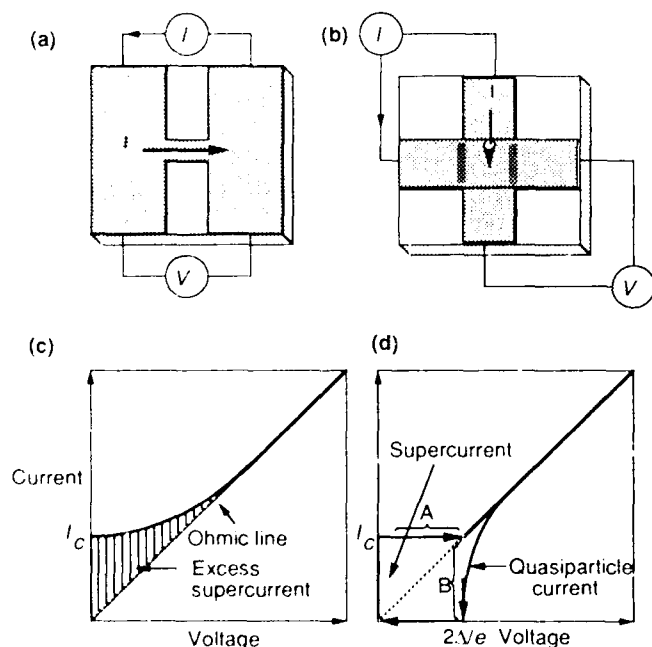


Figure 5 Two common examples of Josephson junctions: (a) microbridge and (b) tunnel junction. Corresponding I - V curves: (c) microbridge I - V curve and (d) hysteretic tunnel junction curve.

¹⁸M. Tinkham, "Junctions: Types, Properties, and Limitations," in *Future Trends in Superconductive Electronics*, AIP Conf. Proc. #44, B. S. Deaver, Jr., C. M. Falco, J. H. Harris, and S. A. Wolf, eds., pp. 269-279 (1978).

models¹⁹ represent the supercurrent response as a phase-dependent inductance given by

$$L_J = \hbar / 4\pi e I_c \cos \Delta\phi, \quad (5)$$

which is illustrated in Fig. 6.

Two important parameters that help to characterize the spatial distribution of the superconducting state and currents and fields in superconductors are the coherence length (at $T = 0$), ξ_0 , and the London penetration depth, λ_L , respectively. The coherence length is a measure of the distance over which the superconducting order parameter varies from a maximum to a minimum value. For a "clean" superconductor it is given by

$$\xi_0 = \hbar v_F / 2\pi^2 \Delta(0). \quad (6)$$

For a "dirty" superconductor ξ_0 is reduced further by a shorter mean free path. The coherence length for the new HTSC materials is considerably shorter than that for conventional LTSC materials (see Table 1) because the energy gap at zero temperature, $\Delta(0)$, for these HTSC materials is significantly larger than that for conventional LTSC materials. The London penetration depth is a measure of the distance over which external magnetic fields penetrate a superconductor, and it is given by

$$\lambda_L = (m^* / \mu_0 n_p e^2)^{1/2}, \quad (7)$$

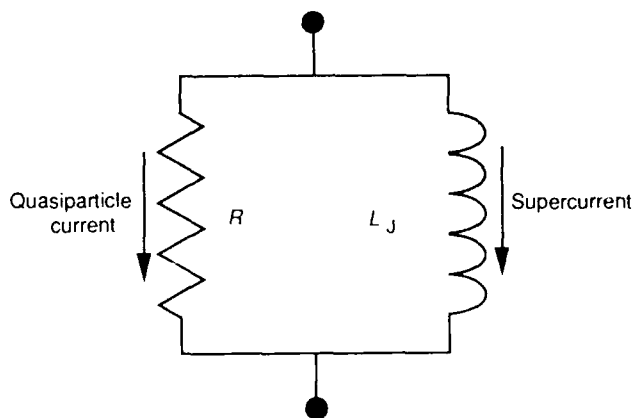


Figure 6 Equivalent circuit model of the intrinsic response of the superconducting weak link (ignoring parasitic effects).

¹⁹A. Barone and G. Paterno, "Voltage Current Characteristics," in *Physics and Application of the Josephson Effect*, John Wiley & Sons, pp. 122-136 (1982).

Table 1
Fundamental superconductor parameters.^{20,21}

Material	Transition temperature, T_c (K)	Energy gap, $2\Delta(0)/e$ (meV)	Coherence length, ξ_0 (nm)	Penetration depth, λ_L (nm)
Lead (Pb)	7.20	2.73	83	37
Niobium (Nb)	9.25	3.05	38	39
YBa ₂ Cu ₃ O _{7-δ}	94	28.4	2.2-3.1 ^{ab} 0.5-0.7 ^c	780-840 ^{ab} 90-95 ^c
BiSrCaCuO	105	31.7	2.7 ^{ab} 0.18 ^c	— — — —
TlCaBaCuO	120	36.2	2.0 ^{ab} 0.03 ^c	— — — —

ab = ab plane, c = c-axis

where m^* and e^* are the pair effective mass and charge, respectively, which are typically taken as twice the electron mass and charge. Typical values for λ_L are given in Table 1 for low- and high- T_c materials. The significance of particular values for ξ_0 and λ_L will be considered later in the report.

A historically important although simplified model of the thermal and electrical behavior of superconductors is the two-fluid model of Gorter and Casimir.²² It describes the basic conduction process in superconductors comprising two interpenetrating fluids or currents—normal and super—each with their respective particle densities n_q (for quasiparticles) and n_p (for paired electrons). The fraction of conduction electrons that are paired varies with temperature according to the relation

$$n_p/n = 1 - (T/T_c)^4, \quad (8)$$

where the total number of carriers $n = n_p + n_q$. Using a formulation of the electrodynamics of superconductors derived by London,²³ a useful model of the high-frequency behavior of superconductors can be developed. Among these models, useful relations are a temperature dependence for the penetration depth

$$\lambda_L(T) = \lambda_L(0) [1 - (T/T_c)^4]^{-1/2} \quad (9)$$

and a complex conductivity given by

$$\sigma = \sigma_1 - j\sigma_2 = n_q e^2 \tau / m [(1 - j\omega\tau)/(1 + \omega^2 \tau^2)] , \quad (10)$$

where m = electron mass and τ is the momentum relaxation time, such that

$$\mathbf{J} = \sigma \mathbf{E} , \quad (11)$$

In the limit of τ approaching infinity, the current density (J) can be written in a form such that the superconductor looks like a pure inductance given by

$$L_{eff} = ml/n_q e^2 A , \quad (12)$$

²⁰F. Y. Fradin, "DOE Programs for Large Scale Applications," Superconductivity Seminar, Wash., D.C. (20 Nov 1987).

²¹R. T. Kampwirth, J. H. Kang, and K. E. Gray, "Superconducting Properties of Magnetron Sputtered Bi-Sr-Ca-Cu-O and Tl-Ba-Ca-Cu-O Thin Films," in *Science and Technology of Thin Film Superconductors*, R. D. McConnell and S. A. Wolf, eds., Plenum Press, pp. 165-173 (1988).

²²C. J. Gorter and H. B. G. Casimir, "On Supraconductivity I," *Physica* **1**, 306 (1934).

²³F. London and H. London, "The Electromagnetic Equations of the Superconductors," *Proc. Roy. Soc. A* **149**, 71 (1935a).

where l and A are the length and cross-sectional area of the superconductor, respectively. The important result for our purposes (Eq. 10) is that at finite frequencies a superconductor acts like a reactive as well as a dissipative system electrically. The dissipative term falls off rapidly at low temperatures and frequencies, as expected, since superconductors should not normally be dissipative.

The two-fluid London model gives a reasonably accurate expression for the surface resistance of a superconductor, which is given by

$$R_s = A(\omega) (T/T_c)^4 [1 - (T/T_c)^4]^{-3/2}, \quad (13)$$

where $A(\omega)$ is proportional to ω^2 . The BCS theory gives

$$R_s = (C\omega^{3/2}/T)\exp[-\Delta(T)/k_B T] + R_0(\omega), \quad (14)$$

provided $\omega \ll 2\pi\Delta(T)/\hbar$ and $T < 0.5 T_c$. The residual surface resistance $R_0(\omega)$ depends on surface quality. An important modern theory that replaces the simplified London and two-fluid models and extends the BCS result is the Mattis-Bardeen theory,²⁴ which accurately accounts for the response of superconductors at all frequencies, including those below and above the energy gap, $\Delta(0)$. From these models, useful relationships for predicting the surface impedance of superconducting transmission line devices can be developed.

²⁴D. C. Mattis and J. Bardeen, "Theory of Anomalous Skin Effect in Normal and Superconducting Metals," *Phys. Rev.* **111**, 412 (1958).

3.0 TECHNOLOGY SURVEY AND ASSESSMENT

3.1 OVERVIEW OF PRIOR ART

Over the last 25 years there have been many developments in the field of superconductivity aimed at practical applications. Several recent reviews and books (Refs. 25-28 and 19, 29-31, respectively) present these developments in great detail. Clarke²⁵ describes the small-scale (microelectronic) applications of superconductivity by dividing them into three broad categories: detection-of-incident (electromagnetic) signals, analog processing of amplified signals, and subsequent digital signal processing. Figure 7 shows examples in each category, with a corresponding hierarchy. In each instance superconducting circuits have been constructed and experimentally evaluated. Those devices highlighted in Fig. 7 have been the most successful in having some degree of use beyond the laboratory.

Before describing some of the more successful applications in detail, I will briefly highlight them here. The SQUID has been the most successful use of superconductivity in reaching commercial development.³¹ Computer logic and microprocessor circuits represent other key areas.²⁸ Although substantial investment was expended by IBM in the late 1970s and early 1980s on the development of a superconducting computer, the project was discontinued because of problems with using lead-based superconducting tunnel junctions for the circuits. At that time niobium-based technology was less mature, but it became more robust with respect to thermal cycling. More recently a superconducting sampling oscilloscope³² has

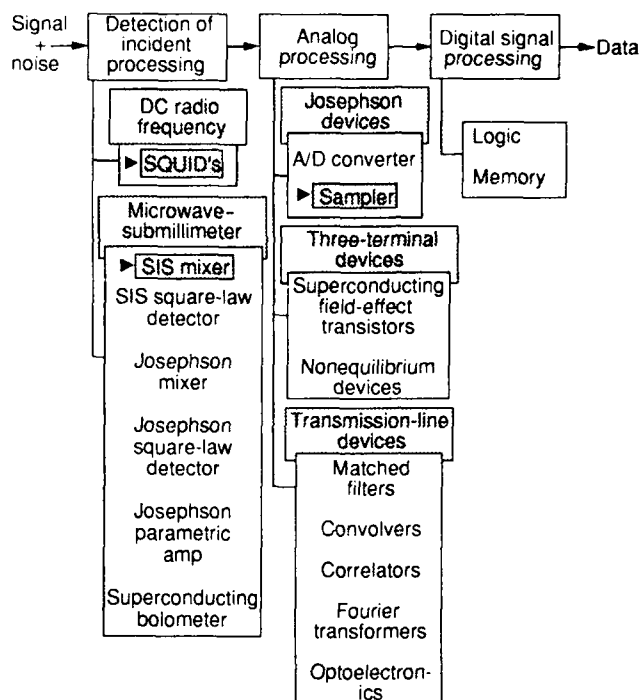


Figure 7 Categories of applications and examples of corresponding superconducting devices (adapted from Ref. 25).

been developed by Hypres, Inc., and has reached commercial use. Hypres was a direct spinoff from the IBM superconducting computer project. Such superconducting integrated circuits can achieve signal sampling bandwidths up to 100 GHz.³³ Superconductor-insulator-superconductor (SIS) mixers have been developed to the point where they are being inserted in the receiver section of radio telescopes.³⁴ They offer the lowest noise performance of any technology. The Josephson voltage standard is also a reasonably successful instrument that has emerged from the laboratory.³⁵

One major practical limitation when using LTSC materials is the need for liquid-helium-based cryocooling. By comparison, the use of liquid nitrogen for HTSC materi-

²⁵J. Clarke, "Small-Scale Analog Applications of High-Transition-Temperature Superconductors," *Nature* **333**, 29 (1988).

²⁶A. P. Malozemoff, "Computer Applications of High Temperature Superconductivity," *Physica C* **153-155**, 1049 (1988).

²⁷Y. G. Vendik and A. B. Kozyrev, "Superconducting Films in Microwave Electronics (Survey)," *Izv. Vyssh. Uchebn. Zaved. Radioelektron.* **26**, 18 (1983).

²⁸N. K. Welker and F. D. Bedard, "Digital Josephson Technology—Present and Future," in *Future Trends in Superconductive Electronics*, AIP Conf. Proc. #44, B. S. Deaver, Jr., C. M. Falco, J. H. Harris, and S. A. Wolf, eds., pp. 425-436 (1978).

²⁹T. Van Duzer and C. W. Turner, *Principles of Superconductive Devices and Circuits*, Elsevier North Holland (1981).

³⁰I. Solymar, "Current-Voltage Characteristics," in *Superconductive Tunneling and Applications*, Wiley-Interscience, pp. 165-185 (1972).

³¹J. Clarke, in *Superconductor Applications: SQUID's and Machines*, B. B. Schwartz and S. Foner, eds., Plenum, N.Y. (1977).

³²"A Practical Way to Turn Out Josephson Junction Chips," *Electronics* **60**, 49-56 (1987).

³³S. K. Pan, A. R. Kerr, M. J. Feldman, and A. W. Kleinsasser, "SIS Technology Boosts Sensitivity of MM-Wave Receivers," *Microwave RF*, 139 (Sep 1988).

³⁴A. Laundrie, "Superconducting IC's Generate and Detect Signals to 100 GHz," *Microwave RF*, 163-164 (Sep 1988).

³⁵R. E. Harris and C. A. Hamilton, "Fast Superconducting Instruments," in *Future Trends in Superconductive Electronics*, AIP Conf. Proc. #44, B. S. Deaver, Jr., C. M. Falco, J. H. Harris, and S. A. Wolf, eds., pp. 448-458 (1978).

als will be cheaper and easier. The latent heat of vaporization is 64 times greater for liquid nitrogen than for liquid helium, and it takes over 30 times less power to maintain a closed-cycle refrigerator at 77 K than at 4.2 K. Conversely the use of LTSC materials requiring liquid helium ensures better noise performance and lower losses at finite frequencies. The importance of noise and conductor losses at a given operating temperature depends on the application, and the actual variation with temperature depends on the type of device.

Among all the applications of the prior art several examples are noteworthy, including the SQUID, microstrip transmission lines, sampling devices, microprocessor logic circuits, far-infrared detectors, and SIS mixers. A brief description of each is given below.

The SQUID's have been made for measuring magnetic flux down to levels of nominally 10^{-13} Wb. To see how small this quantity is in terms of magnetic field, refer to the scale in Fig. 8(a). There are two types of SQUID: the DC and the RF.³⁶ The DC SQUID consists of two

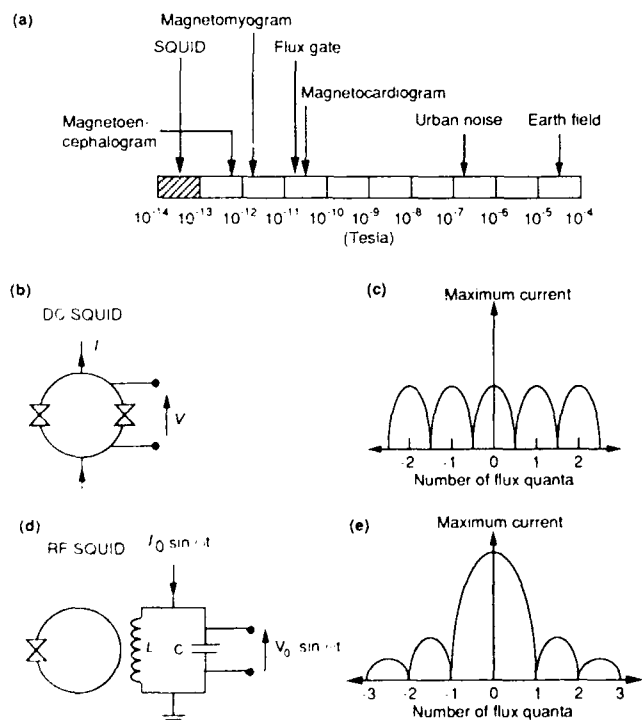


Figure 8 Magnetic flux scale (a) (shown for convenience). Schematic diagram of (b) DC SQUID and (c) corresponding response curve. Schematic diagram of (d) RF SQUID and (e) corresponding response curve.

Josephson junctions coupled in parallel in a superconducting ring as shown in Fig. 8(b). Each junction may be shunted with appropriate inductance and capacitance to avoid a hysteretic I - V curve (an important requirement for SQUID applications). The device is biased with a current to produce a voltage. As the magnetic flux Φ is varied, the voltage oscillates with a period of one flux quantum, Φ_0 . As a result of the variation of the voltage on the I - V curve, the critical current varies periodically with magnetic flux as illustrated in Fig. 8(c). This curve resembles the diffraction pattern created by the two-slit Young's experiment in optics. It is the most sensitive technique for detecting variations in magnetic flux. The RF SQUID, on the other hand, uses a single Josephson junction in a ring inductively coupled via an RF tank circuit to readout electronics, as shown in Fig. 8(d). The resonant frequency of the tank circuit is typically 20-30 MHz. As the magnetic flux Φ through the ring is varied, the amplitude of the RF voltage detected at the output terminals of the tank circuit is modulated with period Φ_0 . The resulting response curve showing the critical current versus magnetic flux is shown in Fig. 8(e). Note that this response curve resembles a single-bit optical diffraction pattern. For both the DC and RF SQUID's, the basic circuits are put into a feedback configuration to obtain a voltage output linearly proportional to applied flux. The SQUID is also versatile as a sensing, interfacing, or switching device for superconducting voltmeters, thermometers, bolometers, and computer circuits.

Analog processing with superconducting transmission lines is another major area that has been investigated in several ways. Simple nondispersive resonators have been built like those illustrated in Fig. 9. High Q factors on the order of 5×10^5 have been achieved using conventional LTSC materials.⁴ These allow highly frequency-stable sources and narrowband filters to be made.^{37,38} Simple microstriplines have been considered for use as interconnects for very-high-speed integrated circuit (VHSIC) computer chips, as suggested in Fig. 10.²⁹ Since VHSIC chips will be dominated by the signal propagation delay between gates, using lower-loss superconducting interconnects should help alleviate this problem because more compact layouts can be achieved with superconductors.

Superconducting transmission lines have also been designed to allow dispersive signal delay to be achieved

³⁶J. Clarke, "Low-Frequency Applications of Superconducting Quantum Interference Devices," *Proc. IEEE* **61**, 8 (1973).

³⁷R. A. Davidheiser, "Superconducting Microstrip Filters," in *Future Trends in Superconductive Electronics*, AIP Conf. Proc. #44, B. S. Deaver, Jr., C. M. Falco, J. H. Harris, and S. A. Wolf, eds., pp. 219-222 (1978).

³⁸R. Davidheiser, "Frequency Stable Sources Using Superconducting Microstrip Resonators," *Proc. 34th Annual Frequency Control Symposium*, USAERADCOM, Ft. Monmouth, N.J. (May 1980).

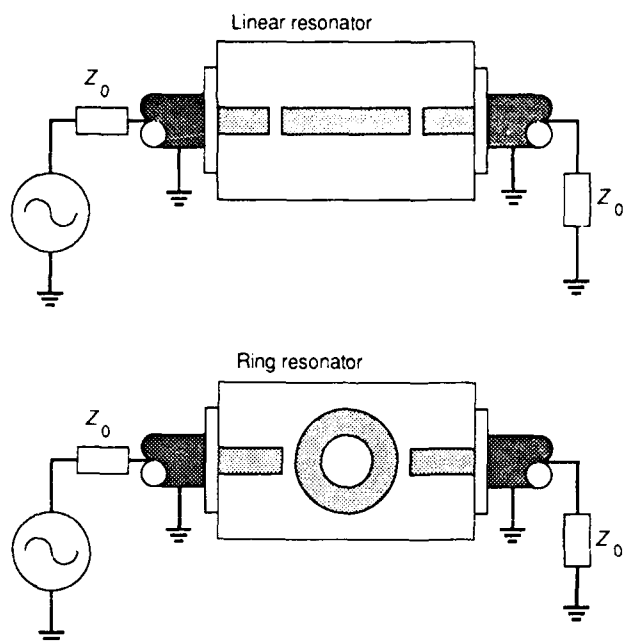
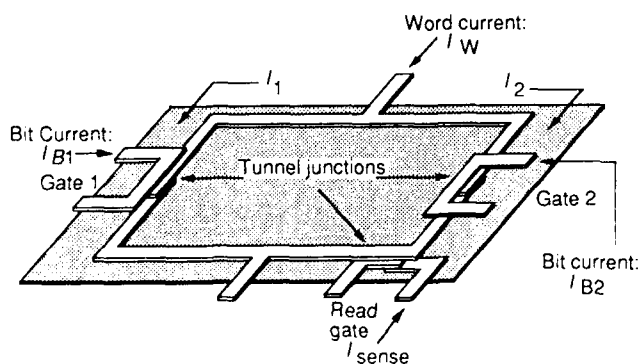


Figure 9 Two examples of simple nondispersive microstrip resonators that can be made using HTSC materials.



Bit currents (I_{B1} and I_{B2}) control states of write junctions (gates 1 and 2).
(Counter) clockwise currents (I_1 and I_2) represent 1's and 0's.
Circulating currents persist after drive currents are removed (nondestructive read-out).
Appearance of voltage in sense line indicates presence of 1 in cell.

Figure 10 Example of superconducting computer memory circuit that could use microstrip interconnects (multiple-flux-quanta memory loop, adapted from Ref. 29).

at microwave (10-GHz) frequencies.³⁹ The construction of these delay lines is illustrated in Fig. 11.^{5,39-41} The delay line is used to store an input signal propagating from left to right. A series of quarter-wavelength backward-wave couplers of varying length reflects incident power back to the input. The resulting output from a series array of these couplers can produce a linearly frequency-modulated chirp, since the resonant length of each coupler varies linearly with distance along the delay line. These devices can be designed into a spiral geometry to make compact chirp generators, which can be used in matched filter receivers and Fourier transformers. Equivalent computation rates of 10^{12} arithmetic operations per second

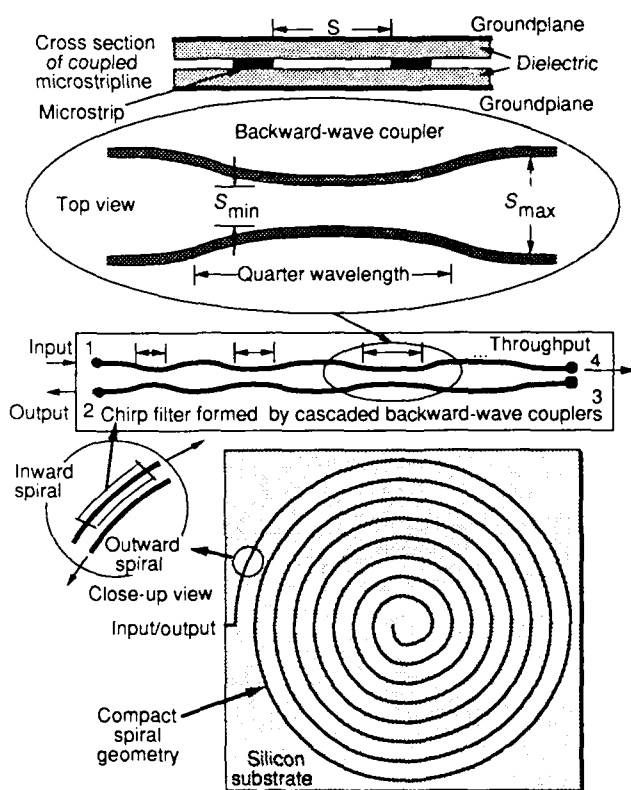


Figure 11 Basic design layout of a superconducting dispersive (chirp) delay line.

³⁹R. S. Withers, A. C. Anderson, P. V. Wright, and S. A. Reible, "Superconductive Tapped Delay Lines for Microwave Analog Signal Processing," *IEEE Trans. Magn.* **19**, 480 (1983).

⁴⁰J. T. Lynch, R. S. Withers, A. C. Anderson, P. V. Wright, and S. A. Reible, "Multigigahertz-Bandwidth Linear-Frequency-Modulated Filters Using a Superconductive Stripline," *Appl. Phys. Lett.* **43**, 319 (1983).

⁴¹R. W. Ralston, "Signal Processing: Opportunities for Superconducting Circuits," *IEEE Trans. Magn.* **21**, 181 (1985).

have been realized. Similar circuits using SIS mixers can be used as signal convolvers.^{42,43}

A fourth class of transmission line device is the "slow-wave" or kinetic inductance device.⁴⁴⁻⁴⁶ Essentially this is a very long meander line,⁴⁷ which is deposited as a very-thin-film pattern on a substrate (see Fig. 12). By making the superconductor thin, the overall inductance of the delay line becomes dominated by the inertial (or kinetic) inductance of the superelectrons rather than by the usual magnetic inductance. Therefore, the phase velocity can be made very small with respect to the velocity of light, hence the name slow-wave delay line.^{48,49} Further, the signal delay can be modulated by varying the phase ve-

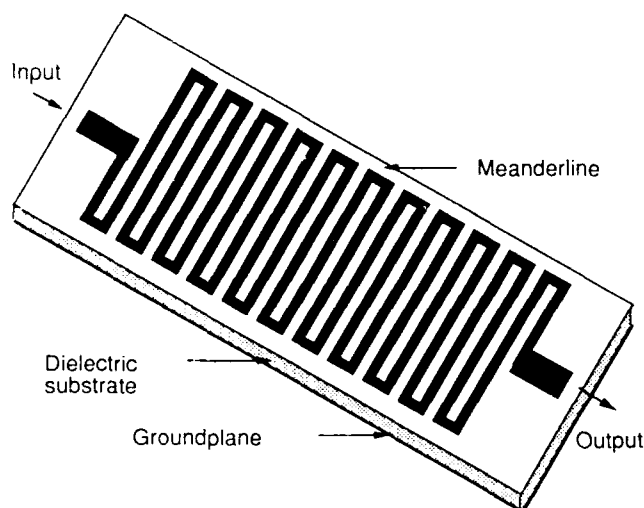


Figure 12 Simple slow-wave meanderline device.

- ⁴²S. A. Reible, A. C. Anderson, P. V. Wright, R. S. Withers, and R. W. Ralston, "Superconductive Convolver," *IEEE Trans. Magn.* **19**, 475 (1983).
- ⁴³S. A. Reible, "Superconductive Convolver with Junction Ring Mixers," *IEEE Trans. Magn.* **21**, 193 (1985).
- ⁴⁴R. Meservey and P. M. Tedrow, "Measurements of the Kinetic Inductance of Superconducting Linear Structures," *J. Appl. Phys.* **40**, 2028 (1969).
- ⁴⁵J. M. Pond, J. H. Claassen, and W. L. Carter, "Kinetic Inductance Microstrip Delay Lines," *IEEE Trans. Magn.* **23**, 903 (1987).
- ⁴⁶J. M. Pond, J. H. Claassen, and W. L. Carter, "Measurements and Modeling of Kinetic Inductance Microstrip Delay Lines," *IEEE Trans. Microwave Theory Tech.* **35**, 1256 (1987).
- ⁴⁷D. A. Gandolfo, A. Boornard, and L. C. Morris, "Superconductive Microwave Meander Lines," *J. Appl. Phys.* **39**, 2657 (1968).
- ⁴⁸P. V. Mason and R. W. Gould, "Slow-Wave Structures Utilizing Superconducting Thin-Film Transmission Lines," *J. Appl. Phys.* **40**, 2039 (1969).
- ⁴⁹J. M. Pond and C. M. Krowne, "Slow-Wave Properties of Superconducting Microstrip Transmission Lines," *IEEE MTT-S Dig.* **1**, 449 (1988).

locity, either by temperature or by direct modulation of the superconducting pair density via incident radiation or quasiparticle injection. Variable phase shifters with application to radar systems can therefore be built.⁵⁰

Sampling devices have been developed that are based on the use of Josephson junctions in which a waveform corresponding to a very-high-speed periodic signal is reproduced from a sequence of samples, each obtained over a very short time interval.⁵¹ The sampling gate is a SQUID that switches to a new state when input current exceeds a certain threshold value I_{th} . The signal current $I_s(t)$ to be sampled is triggered at time $t = 0$ and delayed by an amount τ_g that can be adjusted. At time τ_g a current pulse I_p and bias I_b are added to the signal. When the sum of these currents, $I_s(\tau_g) + I_p + I_b$, exceeds I_{th} , the gate is triggered. Using a feedback circuit the value of I_b can be adjusted to just trigger the gate, so that by varying τ_g a trace of the input signal waveform can be obtained. Sampling resolutions of 2 ps have been obtained. This basic technology has been developed into a fast-sampling oscilloscope (intrinsic bandwidth = 70 GHz) marketed by Hypres, Inc.^{52,53} This instrument can be used to do detailed time-domain reflectometry over millimeter distance scales in MIMIC circuitry. The technology is illustrated in Fig. 13.

A hybrid optoelectronic superconducting sampling device has also been investigated recently that has a time resolution of less than 1 ps.^{52,55} It is illustrated in Fig. 14.⁵⁴ An incident laser beam excites photo-carriers in an appropriate substrate (e.g., silicon) at one end of a niobium stripline, thereby grounding a bias voltage applied to it. The resulting pulse propagates down the line and is then sampled by a second laser beam that shorts one side of the stripline to an electrode. Very-high-bandwidth waveforms can be reconstructed in this manner. A-to-D converters have also been developed based on Josephson

- ⁵⁰S. Baliga, M. Radparvar, and S. M. Faris, "The Superconducting Phase Shifter in the Development of a Terahertz Imaging Radar System," RADC-TR-87-157, Final Tech. Rep. (Oct 1987).
- ⁵¹S. M. Faris, "Generation and Measurement of Ultrashort Current Pulses with Josephson Devices," *Appl. Phys. Lett.* **36**, 1005 (1980).
- ⁵²R. L. Kautz, "Picosecond Pulses on Superconducting Striplines," *J. Appl. Phys.* **49**, 308 (1978).
- ⁵³R. Sobolewski, C. V. Stancampiano, G. Mourou, and D. Butler, "Picosecond Pulse Generation Capability of Optically Driven Superconducting Thin Films," *Phys. Status Solidi* **83**, K203 (1984).
- ⁵⁴C. C. Chi, W. J. Gallagher, I. N. Duling, III, D. Grischowsky, N. J. Halas, M. B. Ketchen, and A. W. Kleinsasser, "Subpicosecond Optoelectronic Study of Superconducting Transmission Lines," *IEEE Trans. Magn.* **23**, 1666 (1987).
- ⁵⁵N. E. Glass and D. Rogovin, "Optical Control of Microwave Propagation in Superconducting Devices," *Appl. Phys. Lett.* **54**, 182 (1989).

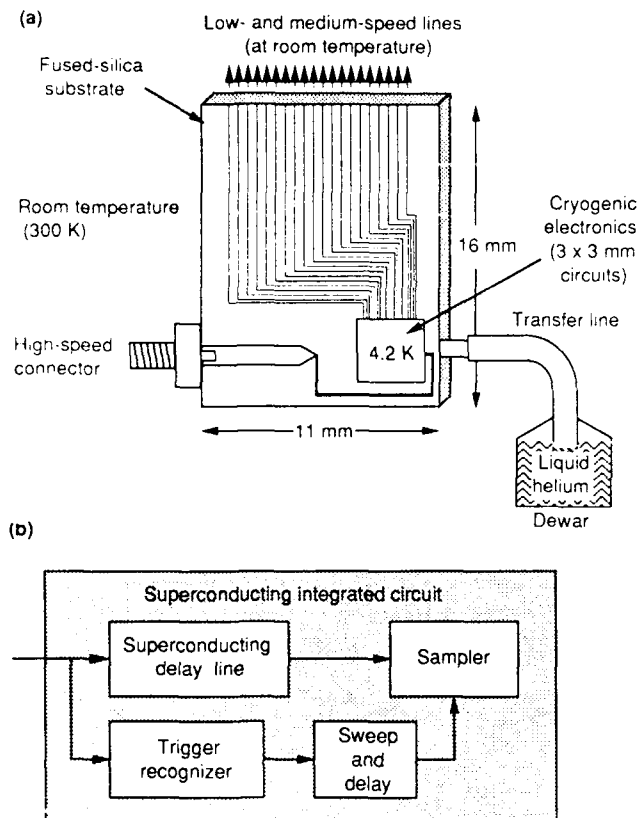


Figure 13 (a) Josephson junction circuit built by Hypres, Inc., cooled by liquid helium spray on one end and at room temperature at the other end; (b) system-level diagram of superconducting integrated circuit (adapted from Ref. 32).

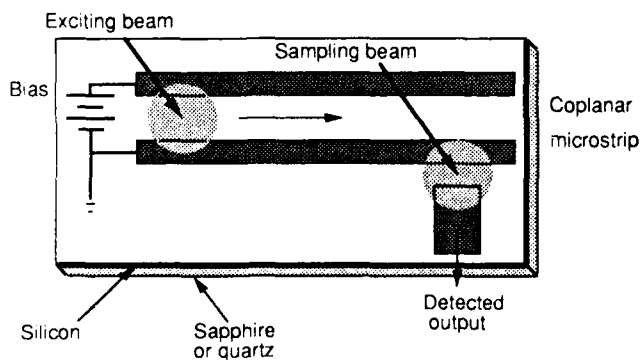


Figure 14 Optically induced waveform sampling using coplanar transmission lines (adapted from Ref. 53).

junctions. In one system based on a DC SQUID, a resolution of 6 bits at 100 MHz has been achieved; resolutions

of 6 bits at 300 MHz and 4 bits at 1 GHz are projected.^{25,56}

Considerable effort was expended by IBM, Bell Labs, and other laboratories in the late 1970s and early 1980s on superconducting logic circuitry. Much of this technology was based on the use of tunnel junctions and SQUID configurations. Switches, memory cells, and Boolean logic gates were constructed.²⁸ Extremely fast switching was obtained from current biasing a Josephson junction so that it was driven into a finite voltage state as shown in Fig. 5a. Switching times of less than 20 ps have been obtained. Josephson junctions also have the lowest power dissipation per gate, on the order of 1 mW or less. Thus the total energy per gate is approximately 10^{-17} J or less. Smaller circuit dimensions can therefore be anticipated because there is less overall power dissipation (consistent with the fact that greater packing density can be achieved by going to superconducting interconnects). By making interconnects out of superconductors, smaller circuit dimensions can be obtained without increasing cross talk between adjacent lines or changing impedance levels from those normally used in semiconducting circuits.

The use of superconducting interconnects will also benefit the interface to semiconductor devices that provide gain, such as that illustrated in Fig. 15. This GaAs MESFET amplifier (and similar high electron mobility transport [HEMT] devices) can operate at high (GHz) frequencies with a lower noise figure using superconducting interconnects.⁸ To compare superconducting versus semiconducting technologies for computing or logic circuits, see Fig. 16, which shows the energy-per-gate regions

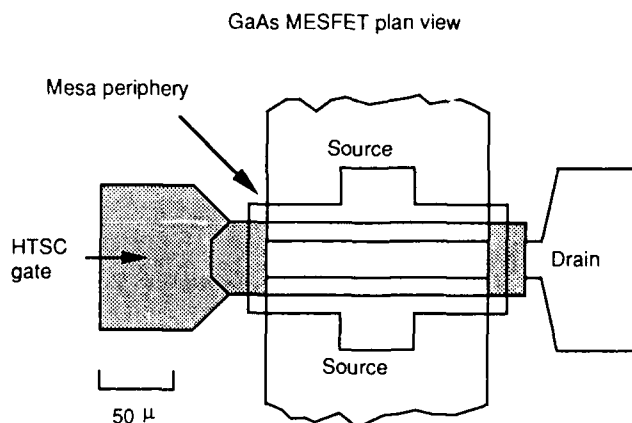


Figure 15 HTSC electrodes can be used as gates for GaAs MESFET amplifiers.

⁵⁶C. A. Hamilton, F. L. Lloyd, and R. L. Kautz, "Superconducting A/D Converter Using Latching Comparators," *IEEE Trans. Magn.* **21**, 197 (1985).

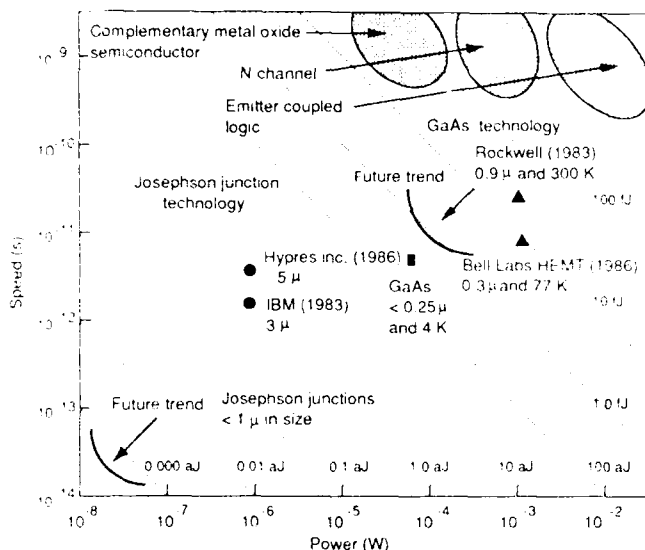


Figure 16 Speed versus power dissipated per gate for various semiconductor and superconductor technologies.

for the various technologies.⁵⁷ We can thus imagine very-high-speed superconducting microprocessors made out of Josephson junctions, superconducting interconnects, and GaAs MESFET amplifiers.

I conclude this section with a discussion of superconducting detectors, which are among the best detectors of electromagnetic radiation of all technologies, especially in terms of their sensitivity and broadband/high-frequency range of operation. Superconducting bolometers have been built that operate on the principle that incident radiation of virtually any wavelength will induce a (typically) resistive transition from the superconducting state to the normal state in a thin piece of superconducting film. The substrate is weakly coupled to a thermal reservoir and has a low heat capacity to yield the best response to incident radiation in the shortest response time. Semiconducting bolometers, however, are very competitive with superconducting bolometers. But, as the fabrication of superconducting thin films is refined to the point where a Josephson junction can be achieved, the superiority of superconducting detectors clearly emerges. The SIS mixers have been developed and installed in radio telescopes operating at frequencies of 100 GHz.³¹ Such devices combine a local oscillator signal with a weak received signal using the highly nonlinear tunnel junction I - V characteristic (shown in Fig. 5d) to produce a difference or intermediate frequency (IF). This nonlinearity occurs at a voltage of $2\Delta/e$. The SIS mixers can be implemented with useful gain and have demon-

strated noise levels within 3 dB of the quantum limit at 36 GHz. To make optimum use of this technology, a fully integrated receiver like that illustrated in Fig. 17 must be built. With an SIS mixer and a low-noise HEMT amplifier, such a system is expected to achieve a 0.14-dB total noise figure.

3.2 POTENTIAL APPLICATIONS

An assessment of potential applications of HTSC devices to microwave and electro-optical systems was conducted in 1988 by panels of the NCS.^{9,10} The panel on high-frequency applications considered the frequency interval from 3 MHz to 100 GHz and applications that exploit the potentially low-RF surface impedance of superconductors and/or RF detection by tunnel junctions.

Actual Navy investment in RF applications of low-temperature superconductivity (e.g., kinetic inductance delay lines, microwave cavities) has been small over the years. No device has ever reached operational status in a Navy system, apparently because the improvement seen over room-temperature devices in RF surface impedance is not sufficient. For detector applications, background-limited performance can already be achieved at room temperature for frequencies up to 30 GHz.⁹

Near-term research and development should focus on understanding and reducing RF surface impedance and making tunnel junctions with reproducible behavior. Larger samples and complex planar and nonplanar geometries are needed for passive microwave devices. For complex geometries as well as tunnel junctions, photolithographic patterning procedures must be perfected. For microwave applications technologically useful substrates must be found that have low dielectric loss, low dielectric constants, and excellent dielectric isotropy (at low tempera-

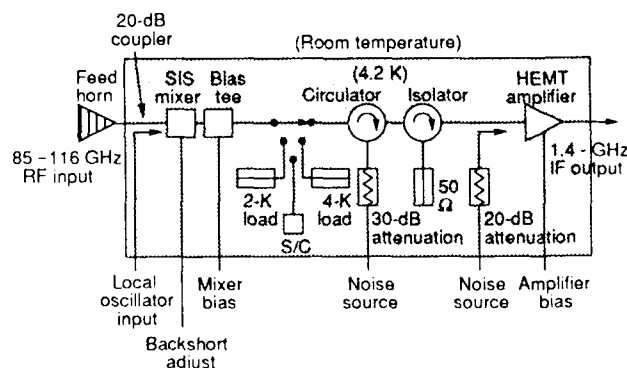


Figure 17 Low-temperature millimeter-wave receiver using superconducting SIS mixer and HEMT amplifier (adapted from Ref. 33).

⁵⁷ "PSP-1000 Picosecond Signal Processor," Hypres, Inc., product brochure (Sep 1986).

tures). For nearly all applications critical current densities of the thin films should be as high as possible (i.e., on the order of 10^5 - 10^6 A/cm²).

Several assumptions were made by the NCS for purposes of a qualitative assessment of the potential application of HTSC materials and devices:

1. RF surface impedance will ultimately equal that obtainable with LTSC films.
2. Reproducible and reliable HTSC tunnel junctions will ultimately be made.

3. Routine cryogenic refrigeration will be acceptable.

Categories of applications considered were:

1. Transmission lines devices,
2. Antennas and antenna arrays,
3. Oscillators,
4. Detectors and receivers, and
5. Digital systems.

For each specific device considered, three areas were evaluated: platform, frequency range, and system type. The results of the assessment are given in Table 2. A "high"

Table 2
NCS assessment of HF applications of
HTSC materials to particular electronic warfare missions.

Device	Platform				Frequency range				System type			
	Sub	Surface	Aircraft	Space	HF	VHF-UHF	Microwave	Millimeter wave	Communications	Radar	ESM	Radiometric
Transmission-line devices												
Cavities and resonators	●	●	●	●	●	●	●	●	●	●	●	●
Diode power combiners	●	●	●	●	○	○	●	●	●	●	●	●
Filters	●	●	●	●	○	○	●	●	●	●	●	●
Low-loss transmission lines	●	●	●	●	●	●	●	●	●	●	●	●
Antennas and antenna arrays												
Electrically small antennas	●	●	○	●	●	●	●	○	●	●	○	N/A
Superdirective arrays	●	●	○	●	●	●	●	○	●	●	○	N/A
Long-wire-transmit antennas	●	●	○	○	●	○	○	○	●	○	○	N/A
Oscillators												
STALO (Stable Local Oscillator)	○	●	○	●	○	●	●	●	○	●	○	●
Navigation time reference	●	●	○	●	← N/A →				○	●	○	●
Detectors and receivers												
RF detector	○	●	○	●	○	○	○	●	●	●	●	●
Focal plane array	○	●	○	●	○	○	○	●	○	●	○	●
Instantaneous frequency measurement	○	●	○	●	●	●	●	●	○	○	●	○
Digital systems												
Chip interconnects	●	●	○	●	●	●	●	○	●	●	●	●
Logic circuits	●	●	○	●	●	●	●	○	●	●	●	N/A
A-to-D converters	●	●	○	●	●	●	●	○	●	●	●	●

potential application for HTSC materials is denoted by a solid circle, a "possible" application (or "situation unclear") by a gray circle, and a "low" potential application by an open circle. From this assessment several conclusions emerge. Applications on space platforms are favored because cooling is essentially free, whereas on all other platforms the enhanced performance gained must be traded off with the complexity of cryogenic refrigeration. The strongest candidates appear to be:

1. Electrically small antennas and arrays,
2. RF detectors and arrays at millimeter-wave frequencies, and
3. High-speed digital circuits.

In addition, oscillator and transmission-line applications are viable if cryogenics are required for other reasons.

From the NCS HF assessment summarized in Table 2 some inferences can be drawn. Of the three categories evaluated (platform, frequency range, system type), a priority can be attached to the types found in each category as shown in Table 3.

Table 3
Inferences from the NCS HF assessment.

Platform	Frequency range	System type	Priority
Surface	Microwave	Radar/ communications	1
Space	HF/VHF/UHF	Electronic support measures/ radiometric	2
Sub	Millimeter wave	— —	3
Aircraft	— —	— —	4

One can infer that the best combination of categories for the application of HTSC technology is to surface platforms operating in the microwave spectrum for radar and/or communications. The next best combination, however, is not space, HF/VHF/UHF, and electronic support measures/radiometric, since the categories are independent. Application to space, in the microwave spectrum for radar/communications, might be one possible second choice.

Looking at the broad range of generic device/systems, the priorities and grades for potential HTSC technology insertion are given in Table 4.

Table 4
Rating of generic categories from the
NCS HF assessment.

Category evaluated	Priority	Grade
Digital systems	1	88%
Transmission-line devices	2	81%
Oscillators	3	79%
Antennas and arrays/ detectors and receivers	4	60%

The view of the NCS subpanel on HF applications is that digital systems are the preferred application of HTSC technology by a significant margin. Transmission-line devices (e.g., microstrips) and oscillators are second and third, but are almost indistinguishable on the basis of grade. Antennas and arrays/detectors and receivers are a distant fourth. The problems with this type of assessment are that the prognostications soon become outdated, underlying assumptions and/or evaluation criteria are ambiguous or unknown, and considerations may not be given to emergent applications and novel designs, which constitute exceptions to the general categories assessed. Thus it is difficult to predict the future progress of HTSC technology.

When considering potential electro-optical applications of HTSC materials a different set of characteristics is required.¹⁰ The most important application is probably infrared (IR) focal plane arrays (FPA's). The requirements for several parameters and characteristics can be specified, as shown in Table 5.

Despite the wavelength limitations imposed by atmospheric transmission, the illustration of wavelength coverage in Fig. 18, showing HTSC versus other technologies, implies that HTSC detectors could be operated at virtually any wavelength from near-IR (1 μm) to 100 μm and below. But this illustration ignores the relative sensitivity of HTSC detectors, which depends critically on the mode of operation and the ambient device temperature. Figure 19 compares sensitivity as measured by detectivity (D^*); the higher the D^* , the better the sensitivity. By comparison, a recent measurement using YBCO is not competitive with prior technology,⁵⁸ whether semiconductor

⁵⁸M. Leung, P. R. Broussard, J. H. Claassen, M. Osofsky, S. A. Wolf, and U. Strom, "Optical Detection in Thin Granular Films of Y-Ba-Cu-O at Temperatures between 4.2 and 100 K," *Appl. Phys. Lett.* **51**, 2046 (1987).

Table 5
NCS Assessment of IR FPA requirements.

Parameter/characteristics	Requirements
Wavelength	3-5 μm , 8-12 μm (atmospheric) 1-40 μm (space)
Sensitivity/detectivity	Background-limited performance
Cost/manufacturability	Uniformity of processing across wafer Insensitivity to defects, impurities, and high temperatures during fabrication
Operating temperature	As high as possible (e.g., ≥ 77 K, consistent with performance)
Response time	MHz response for free space sensors GHz response for fiber optics
Integration/complexity	Hybrid-acceptable, Monolithic preferred Large Sensor Array TV format and multicolor display desirable
Signal processing	12-14 bits A/D at 10 MHz 10^7 - 10^{10} operations/s

or superconductor. The particular sample considered, however, was a preliminary experimental result, which had not been designed with optimum materials or fabrication processes.

The recommendations of the NCS panel for IR applications focused on the evaluation of HTSC materials as sensors. Factors of sensitivity, response time, wavelength selectivity, and cost/manufacturability were considered. The panel made several recommendations. Detectivity D^* must be determined versus material and material characteristics, operating temperature, and wavelength.

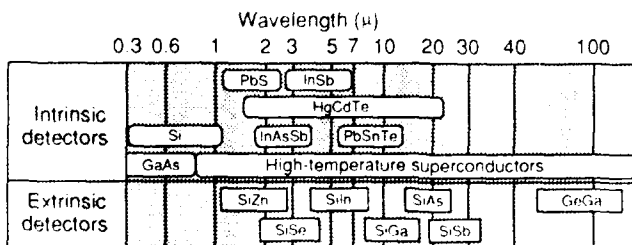
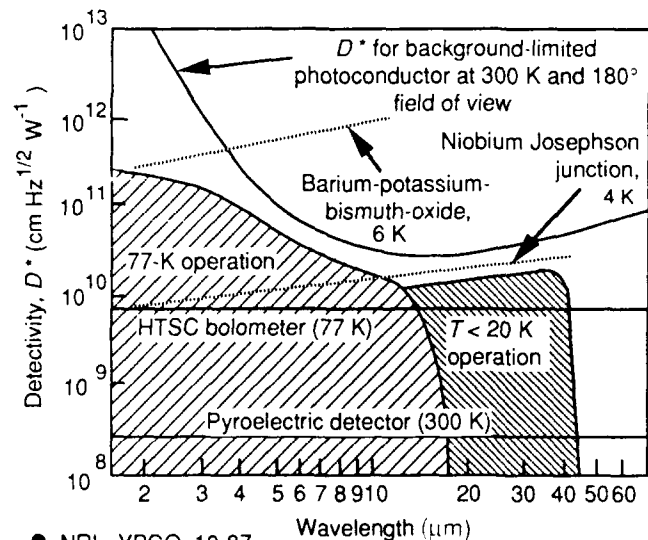


Figure 18 Comparison of wavelength coverage of HTSC and semiconducting detector technologies.



• NRL YBCO 10-87

Figure 19 Comparison of the sensitivity of superconducting detectors at various temperatures against an ideal room-temperature semiconducting photoconductor.

Cost-manufacturability issues should include: consideration of the materials-processing equipment required, sensitivity of the detectors to defects and impurities in the thin films, and the differences between polycrystalline and single-crystal devices. Further, signal-processing requirements and the use of compatible (HTSC) post-detection signal-processing chips should be evaluated.

Potential applications anticipated for HTSC detectors include exoatmospheric systems for surveillance, acquisition, tracking, imaging, and far-IR astronomy, as well as laboratory instrumentation for IR spectroscopy and nondestructive testing. The most likely near-term use of HTSC detectors may be in laboratory instrumentation because the signal-to-noise ratio requirement is fairly benign. Space application of HTSC detectors is also attractive because their broad spectral response is not compromised as it would be in the presence of atmospheric transmission bands, and cooling is essentially free.

3.3 CURRENT RESEARCH AND DEVELOPMENT

Current research and development activity recently reported in the open literature, which is geared towards applications of HTSC materials, tends to focus on

- Bolometric detection
- Passive RF microwave devices
- Josephson junctions and SQUID's
- RF microwave properties of HTSC materials
- Granular superconductor properties

Not surprisingly, API's projects are oriented largely toward these same areas. A summary of the current work of other investigators is given below.

Recent work at the Naval Research Laboratory (NRL) has demonstrated that it is feasible to use YBCO in an optical detector operating at temperatures as high as 100 K.⁵⁹ A rapid-response bolometric element was constructed from granular films of YBCO of 1- μ m thickness, rise time of 20 ns, D^* of 10^6 cm Hz^{1/2}/W, and noise equivalent power (NEP) of 1 μ W. A 900-K blackbody source chopped at 17 Hz and a HeNe laser were used in conjunction with quartz windows, which filter the blackbody source over a range of wavelengths that exclude 3-60 μ m, a spectral region where HTSC materials might work best. The NRL investigators believe that the granular-film response can be attributed to a phase-slip process rather than a bolometric effect. A peak in the response to blackbody radiation was observed at lower temperatures (\sim 30 K). In addition, the investigators indicated that the main noise source was probably shot noise caused by the contacts. A simple network was used to bias the bolometer and transfer its output to a lock-in amplifier.

Other investigators at Westinghouse R&D Center⁵⁹ recently measured the optical response of epitaxial films of YBCO at HeNe- and CO₂-laser wavelengths. In contrast to the NRL results, these films do not exhibit the nonequilibrium (phase-slip) process of granular films, but merely a bolometric response, which occurs at the transition temperature ($T_c = 25$ -60 K). This suggests that epitaxial films do not consist of multiple weak-link arrays, which could be modulated by incident radiation. These epitaxial films were fabricated into bridges with dimensions of 10 μ m by 90 μ m. The HeNe source was chopped at 725 Hz. A responsivity of 4×10^3 V/W and a detectivity of $D^* \geq 10^5$ cm Hz^{1/2}/W were obtained. The rise time of the bridge was reported to have two components: a "fast" portion (\sim 1 μ s) and a "slow" portion (\sim 1 ms). The noise spectrum exhibited a "1/f" roll-off, but the investigators indicated that it may not be entirely intrinsic to the bridge. The nonequilibrium response of the films is expected since they are epitaxial, have a high critical current density ($J_c \sim 2 \times 10^6$ A cm⁻²), and have a slower response characteristic of a thermally activated device. Important and interesting work is going on at other laboratories (see Refs. 60-62), but the work described above is representative of the significant new efforts in this area.

Passive microwave devices, particularly resonators and delay lines, are receiving attention from many investigators. Fathy et al.⁶¹ summarize recent progress in superconducting resonators, which is given in Table 6. The principal requirement for making low-loss (high-Q) microstrip thin-film devices, as discussed earlier, is low RF surface resistance, and this is certainly the major concern of today's efforts. A summary of recent measurements is given in Fig. 20, showing surface resistance versus frequency for copper at several temperatures and the 1-2-3 ceramic at 77 K. These results suggest that the HTSC materials are not yet ready for applications, since the 1-2-3 losses are not significantly different from copper at the desired operating temperatures (\sim 77 K). New results on thallium-

⁵⁹M. G. Forrester, M. Gottlieb, J. R. Gavaler, and A. I. Braginski, "Optical Response of Epitaxial Films of YBa₂Cu₃O_{7-x}," *Appl. Phys. Lett.* **53**, 1332 (1988).

⁶⁰H. J. Goldsmid, K. K. Gopinathan, D. N. Matthews, K. N. R. Taylor, and C. A. Baird, "High- T_c Superconductors as Passive Thermo-Elements," *J. Phys. D: Appl. Phys.* **21**, 344 (1988).

⁶¹Y. Enomoto, T. Murakami, and M. Suzuki, "Infrared Optical Detector Using Superconducting Oxide Thin Film," *Physica C* **153-155**, 1592 (1988).

⁶²P. L. Richards, J. Clarke, R. Leoni, P. Tercl, S. Verhese, M. R. Beasley, I. H. Gabelle, R. H. Hammond, R. Rosenthal, and S. R. Spielman, "Feasibility of the High T_c Superconducting Bolometer," *Appl. Phys. Lett.* **54**, 283 (1989).

⁶³A. Fathy, D. Kalokitis, and E. Belohoubek, "Microwave Characteristics and Characterization of High T_c Superconductors," *Microwave J.* **31**, 75-94 (Oct 1988).

Table 6
Recent research results in HTSC resonators.

Source	Characterization technique	Measurement frequency	Material properties
Stanford UCLA	Cylindrical cavity	100 GHz	Magnetron co-sputtered on SrTiO ₂ , $T_c = 90$ K
MIT Lincoln Lab	Stripline resonator	0.5-18 GHz	E-beam layered on Y-ZrO ₂ , $T_c = 72$ K
David Sarnoff Research Center Rutgers	Disk resonator	10 GHz	Bulk material, $T_c = 92$ K
Northeastern	Cylindrical cavity	9.8 GHz	Bulk material, $T_c = 92$ K
Cornell AT&T	Cylindrical Nb cavity perturbed by HTSC material	6 GHz	Crystal platelets, $T_c = 89$ K

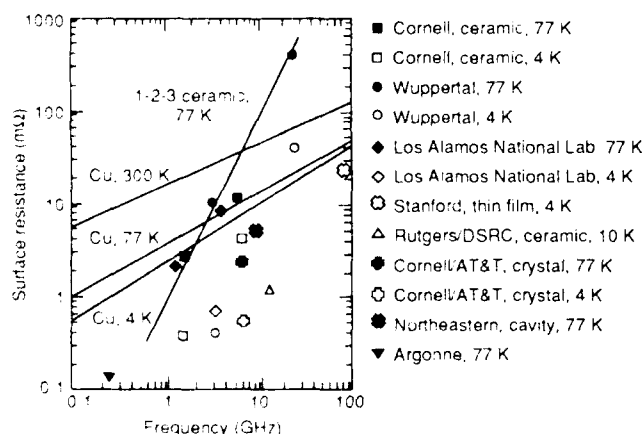


Figure 20 Plot of calculated surface resistance versus frequency for 1-2-3 ceramic (YBCO) superconductors along with recent measurements and comparison to calculations for copper at various temperatures (Ref. 63).

barium-calcium-copper-oxide and YBCO indicate surface resistance losses 1 and 2 orders of magnitude less than copper at 77 K at 148 and 10 GHz, respectively.^{64,65} The ma-

jor obstacles to achieving better results are obtaining smoother epitaxial films, lower-loss, low-anisotropy substrates, and effective low-temperature, low-loss packaging. On the basis of the above measurements and predictions using simple theoretical models, applications to delay lines and interconnects may be limited. This pessimistic outlook may be ameliorated by improvements in fabrication technology. For instance, if Q values can be improved by factors 100 or more over copper at 77 K, there should be sufficient reason to implement passive HTSC microwave components in actual systems.

Making use of the property of lower loss is not the only approach to exploiting HTSC stripline components. Because of the granular nature of HTSC films, detection and mixing of microwave signals can be accomplished. Recent experiments with YBCO microstrips at 24 GHz have demonstrated very fast response times (~ 40 ps).⁶⁶ The results indicate that an enhanced nonbolometric mode of detection is occurring, with a speed of response limited only by the superconducting energy gap. Another potential application of HTSC materials noted previously uses the kinetic inductance effect of thin superconducting microstrip delay lines.⁵⁰ By modulating the quasiparticle density in HTSC microstrips, variable phase-velocity lines can be used to implement variable phase shifters. Since nonequilibrium quasiparticle density is modulated to achieve variable phase delay and limited only by the gap frequency (which is much higher for HTSC than LTS materials), the up-

⁶⁴W. L. Olson, M. Eddy, I. W. James, McD. Robinson, D. D. P. Casavant, E. J. Smith, A. Cardona, and R. B. Hammond, "Low Surface Resistance Thin Films of $Tl_2Ca_2Ba_2Cu_3O_{10}$ Produced by Chemical Deposition and Laser Ablation," Workshop on High Temperature Superconductivity, Huntsville, Ala. (23-25 May 1989).

⁶⁵D. H. Wu, W. L. Kennedy, C. Zahopoulos, and S. Sridhar, "Characteristics and Growth of Single Crystals of $Y_1Ba_2Cu_3O_7$ with Superior Microwave Properties," *Appl. Phys.* **55**, 696 (1989).

⁶⁶J. Konopka, R. Sobolewski, A. Konopka, and S. J. Lewandowski, "Microwave Detection and Mixing in Y-Ba-Cu-O Thin Films at Liquid-Nitrogen Temperatures," *Appl. Phys. Lett.* **53**, 796 (1988).

per frequency limit of these devices should be much higher (i.e., 700 GHz [for niobium] versus approximately 5 THz [for materials such as BSCCO]).

Attempts to achieve a measurable Josephson effect in YBCO and BSCCO films have been reported. Although "break" junctions have been made,⁶ thin-film tunnel junctions and microbridges are of the greatest interest. Multilayered YBCO films have been fabricated recently on yttria-stabilized zirconia using a screen printing method. These films show typical weak-link I - V characteristics at 4.2 K and 12 K; T_c 's are ~ 90 K.^{6a} The implications of these measurements are that naturally occurring (microscopic) tunnel barriers form between neighboring high- T_c grains, and that it is these structures rather than the (mesoscopic) artificial barrier that produce the observed I - V characteristics. The artificial barrier, however, has been shown to survive subsequent fabrication processing.

Other investigators have reported grain-boundary Josephson junction array-type microbridges using 1-2-3 materials^{6b,7} as well as similar $\text{BaPb}_{1-x}\text{Bi}_x\text{O}_3$ (BPBO) materials.^{7a} Microwave-induced steps on the I - V characteristics of YBCO thick films have been observed at 77 K.^{6c} These bridges are 100 μm long, ≥ 200 μm wide, and 30 μm thick. The maximum grain size is typically 70 μm . Thin epitaxial films with mixed orientation

have also been fabricated on strontium titanate using DC magnetron sputtering/thermal evaporation for deposition and photoresist lift-off for patterning.^{7b} These bridges have widths down to 2 μm , lengths of 200 μm , and thicknesses of ~ 500 nm. Typical T_c 's of 88 K are achieved. Ion-mill etching is used to weaken the bridges before testing. Nonlinear I - V characteristics as well as energy-gap structure have been observed up to 33 K, but no explicit indication of Josephson behavior has been seen (e.g., microwave-induced steps on the I - V characteristic).

Although many others have begun investigating these types of weak-link structures, the above examples highlight current research. The key requirement in the fabrication of weak links is achieving control, not only of the pattern geometry but of the grain-size distribution relative to the geometry. As better reproducibility of transport characteristics is achieved, higher yield will probably follow. For tunnel junctions it is essential to control the surface layer between the two superconducting sides.^{7c} That layer must be clean and virtually defect-free.

Despite the quality control concerns for fabricating weak-link structures, functioning SQUID devices have been made. IBM has made DC SQUID's from YBCO on MgO and SrTiO_3 (100) substrates.^{7d} The films were patterned using ion implantation, laser ablation, and ion milling. These polycrystalline film patterns have large critical dimensions with respect to the superconducting coherence length, and therefore exhibit Josephson junction behavior based on the collective response of multiple grain-boundary weak links. The noise from a SQUID on MgO operated at 40 K was $\sim 10^{-6} \Phi_0/\text{Hz}^{1/2}$ at 1 KHz, and another device operated as a DC SQUID exhibited a noise of $10^{-3} \Phi_0/\text{Hz}^{1/2}$ at 74 K. Average grain size in these films was 2-5 μm . Other investigators have made DC SQUID's.^{7e,80} Very recently, planar weak-link devices, including SQUID's, have been made from BSCCO (as well as YBCO) on MgO substrates, as reported by inves-

^{6a} L. Moreland, L. E. Goodrich, J. W. Ekin, T. E. Capobianco, A. L. Clark, A. L. Braginski, and A. J. Panson, "Josephson Effect above 77 K in a YBaCuO Break Junction," *Appl. Phys. Lett.* **51**, 540 (1987).

^{6b} T. Yamashita, A. Kawakami, S. Noge, W. Xu, M. Takada, T. Komatsu, and K. Matusita, "Josephson Effects at 77 K in Grain Boundary Bridge Made of Thick Films," *Jap. J. Appl. Phys.* **27**, L1107 (1988).

^{6c} M. G. Blamire, G. W. Morris, R. E. Somekh, and J. E. Evetts, "Fabrication and Properties of Superconducting Device Structures in YBa₂Cu₃O_{7-x} Thin Films," *J. Phys. D: Appl. Phys.* **20**, 1330 (1987).

^{6d} G. C. Hilton, E. B. Harris, and D. J. Van Harlingen, "Growth, Patterning, and Weak Link Fabrication of Superconducting YBa₂Cu₃O_{7-x} Thin Films," *Appl. Phys. Lett.* **53**, 1107 (1988).

^{6e} P. England, T. Venkatesan, X. D. Wu, A. Inam, M. S. Hegde, T. L. Cheeks, and H. G. Craighead, "Intrinsic Superconductor Normal-Metal Superconductor-like Weak Links in YBaCuO_{7-x} Thin Films," *Appl. Phys. Lett.* **53**, 2336 (1988).
^{7a} Y. Enomoto and T. Murakami, "Infrared Optical Detectors Using BPB Films," *Rev. Elec. Commun. Lab.* (NTT, Japan) **34**, 263 (1986).

^{7b} Y. Enomoto and T. Murakami, "Optical Detector Using Superconducting BaPb_{1-x}Bi_xO₃ Thin Films," *J. Appl. Phys.* **59**, 3807 (1986).

^{7c} T. Murakami, M. Suzuki, and K. Moriawaki, "Some Phenomena in a Boundary Josephson Junction (BPB) Array," *Rev. Elec. Commun. Lab.* (NTT, Japan) **34**, 257 (1986).

^{7d} M. Suzuki, T. Murakami, and Y. Enomoto, "Boundary Josephson Junctions in BaPb_{1-x}Bi_xO₃ (BPB) Polycrystalline Film," *Rev. Elec. Commun. Lab.* (NTT, Japan) **34**, 249 (1986).

^{7e} J. Takada, T. Terashima, Y. Bando, H. Mazaki, K. Iijima, K. Yamamoto, and K. Hirata, "Tunnel Junctions Using Oxide Superconducting Thin Films Epitaxially Grown on SrTiO₃," *Appl. Phys. Lett.* **53**, 2689 (1988).

⁸⁰ R. H. Koch, C. P. Umbach, M. M. Oprysko, J. D. Mannhart, B. Bumble, G. J. Clark, W. J. Gallagher, A. Gupta, A. Kleinbasser, R. B. Laibowitz, R. B. Sandstrom, and M. R. Scheuermann, "DC SQUID's Made from YBa₂Cu₃O_{7-x}," *Physica C* **153-155**, 1615 (1988).

^{7f} C. M. Pegrum, G. B. Donaldson, A. H. Carr, and A. Hendry, "Observation of Quantum Interference Effects and SQUID Operation in a Bulk Sample of YBa₂Cu₃O_{7-x} at 7.7 K and 4.2 K," *Appl. Phys. Lett.* **51**, 1364 (1987).

^{7g} C. E. Gough, "Flux Quantization and SQUID Magnetometry Using Ceramic Superconductors," *Physica C* **153-155**, 1569 (1988).

^{7h} U. Kawabe, "Application of High-Temperature Superconductors to SQUID's and Other Devices," *Physica C* **153-155**, 1586 (1988).

tigators at Rockwell International Science Center.⁸¹ The length and width of the weak-link constrictions were in the range of 5–10 μm ; the thickness was 0.5 μm , and the SQUID areas were 25 $\mu\text{m} \times 25 \mu\text{m}$. T_c 's were 65 K (for BSCCO films). Measurable SQUID modulation patterns were observed up to 30 K, and root-mean-square flux noise was $2.5 \times 10^{-2} \Phi_0$ in a 0.001–0.2-Hz bandwidth.

An important consideration in the design of HTSC SQUID's is predicting their sensitivity. Predictions of DC SQUID sensitivity at 77 K by Pegrum et al.⁷⁸ show a flux noise of $10^{-4} \Phi_0/\text{Hz}^{1/2}$, which appears to be pessimistic on the basis of recent measurements. These measurements, which were summarized by Gough,⁷⁹ are repeated in Table 7.

Some recent theoretical work addresses the modeling of HTSC thin-film response to microwaves as well as high-frequency losses.^{42,83} A model of Josephson coupling between grains can be used to explain millimeter-wave surface impedance in oriented, polycrystalline films. Effective junction $I_c R$ product and effective grain size are calculated on the basis of measurements of surface impedance.⁸⁴ The voltage response of thin-film detectors made from perovskite-type superconductors can also be explained on the basis of multiple grain-boundary Josephson junction models. Essentially the voltage change has a power-law dependence on incident optical power, the exponent of which depends on the presence of multiple weak links with a prescribed critical current distribution.⁶¹ One characteristic of this area of investigation is that many quantities that are calculated cannot be measured directly, and many quantities that can be measured are difficult to calculate

from theory.⁸⁵ Certainly DC transport measurements and possibly measurements of the complex impedance can be tied to the theory. The importance of these models is in their utility for explaining the limits of device performance when using granular films, especially in determining how much noise or chaotic behavior can be expected in films with a particular grain-size distribution.⁸⁶

In summary, the most important avenues of investigation lie in the materials-processing domain rather than in the design of unique devices, since so many of the device concepts have already been developed using LTSC materials. Controlling the geometry through effective patterning techniques is expected. Controlling the grain-size distribution, and, in fact, eliminating grains is highly desirable. Minimizing the surface roughness and defects, especially for microwave applications, is vital. Further, using smooth, low-loss substrates is also important in microwave applications.

Table 7
Recent results for flux noise in RF and DC SQUID's.

Type of device	Temperature (K)	Flux noise ($\Phi_0/\text{Hz}^{1/2}$)	B-field noise (T/Hz ^{1/2})
RF SQUID's			
Typical commercial	4.2	5×10^{-5}	$\sim 10^{-13}$
Bulk SQUID			
Ceramic	77	1.5×10^{-3}	1.5×10^{-10}
	77	5×10^{-3}	10^{-9}
1-hole crack junction	77	4.5×10^{-4}	10^{-12}
2-hole w/constriction	77	10^{-3}	2×10^{-12}
DC SQUID's			
At liquid helium	4.2		$\sim 10^{-14}$
Constriction	77	9×10^{-9}	1.2×10^{-12}
Thin film	60	6×10^{-3}	$\sim 2 \times 10^{-9}$

⁸¹I. S. Gergis, J. A. Titus, P. H. Koblin, and A. B. Harker, "Planar Weak-Link Devices from YBaCuO and BiSrCaCuO Films," *Appl. Phys. Lett.* **53**, 2226 (1988).

⁸²L. A. Hornak, S. K. Tewksbury, and M. Hatamian, "The Impact of High- T_c Superconductivity on System Communications," in *Proc. 38th Electronic Components Conf.*, pp. 152–158 (9–11 May 1988).

⁸³T. L. Hylton, A. Kapitulnik, M. R. Beasley, J. P. Carini, L. Drabek, and G. Gruner, "Weakly Coupled Grain Model of High-Frequency Losses in High T_c Superconducting Thin Films," *Appl. Phys. Lett.* **53**, 1343 (1988).

⁸⁴J. P. Carini, A. M. Awasthi, W. Beyermann, G. Gruner, T. Hylton, K. Chan, M. R. Beasley, and A. Kapitulnik, "Millimeter-Wave Surface Resistance Measurements in Highly Oriented YBaCuO_{2-x} Thin Films," *Phys. Rev. B* **37**, 9726 (1988).

⁸⁵C. J. Lobb, "What Can (and Can't) Be Measured in Superconducting Networks," *Physica B* **152**, 1 (1988).

⁸⁶M. A. H. Nerenberg, J. H. Beasley, and J. A. Blackburn, "Chaotic Behavior in an Array of Coupled Josephson Weak Links," *Phys. Rev. B* **36**, 8333 (1987).

4.0 REQUIREMENTS FOR TECHNOLOGY DEVELOPMENT

As technologists and system engineers begin to consider the promises of HTSC materials, a critical assessment will begin that will bear fruit in useful applications. Two areas where superconductivity shows strong promise are in electro-optical and electronic warfare. Although electronic warfare offers good opportunities for HTSC device application, requirements are stringent for signal detection, sampling, and processing. Electro-optical systems for surveillance and tracking, especially when operated in space, offer a potentially favorable environment for superconducting sensors with equally demanding requirements. HTSC materials and devices may provide considerable gains over conventional materials and devices in these areas.

Electronic warfare involves many techniques for dealing with the electronic battlefield, whether the goal is radar detection, electronic countermeasures (ECM), electronic counter-countermeasures (ECCM), or electronic support measures (ESM). Both jamming and deception, either of which can be enabled by transmitted or reflected RF energy, are the concerns of ECM. Of course ECCM techniques are tailored specifically to the particular ECM threat. The purpose of ESM is to passively listen, detect, identify, and determine the direction of radar signals. It can provide warning of radar tracking and/or missile launch, as well as the control of ECM (i.e., enable deception ECM to be maintained after a threat missile is launched). It can also support radar signal processing and ECM with signal sorting.

Electro-optical warfare hinges primarily on achieving good detector sensitivity and minimizing the degrading effects of system losses, particularly for passive receiver systems. The goal is to detect targets at the greatest possible range, which have the lowest intrinsic contrast. Typical systems include single-detector reticle-type nonimaging sensors as well as scanning or staring-type imaging sensors. These detectors or detector arrays also require considerable signal processing to actually perform detection, tracking, and imaging functions. Application to air- and space-vehicle guidance and surveillance are well known.

4.1 SYSTEM APPLICATION REQUIREMENTS

Historically military applications of radar have provided the basis for electronic warfare. Once a new radar system is developed an electronic means is developed to counter it. There are several ways to counter radar systems. The more common techniques include decoys, chaff, and jammers. To effectively interfere with a radar, how-

ever, means of detecting, locating, and characterizing the radar must also be devised. Systems that do this are electronic warfare receivers. The types of systems of possible interest include both active ECM, such as jammers and decoys, and traditional electronic warfare systems, such as radar warning and ESM receivers.

The principal requirement of an electronic warfare system is the ability to perform effective radar detection, which requires a low-noise receiver (comprising antenna, preamplifier, and detector). The signal that is subsequently used for system response depends on several factors, including receiver gain, range to target or source, and target radar cross section or effective radiated power of the source. The total system noise depends on the environment and receiver noise. Of all these factors, only the characteristics of the receiver are under the control of the system designer. To maximize the signal-to-noise ratio it is generally desirable to maximize the signal by maximizing the gain of the receiver while maintaining or reducing noise by narrowing the receiver bandwidth. Increased receiver gain can be obtained by reducing losses, especially conductor losses. Obviously this is the rationale for the use of HTSC materials. To reduce intrinsic receiver noise (considered to be primarily thermal noise) it is also obvious that reducing the temperature to accommodate the use of HTSC materials will be beneficial.

In attempting to deceive threat radars, an electronic warfare system must react quickly to the threat radar signature. The waveform incident on the receiver must be sampled and analyzed for ESM purposes or reconstructed for ECCM purposes very quickly—on the order of the pulse-repetition interval or the pulse-width interval, respectively. Current and future threats drive the need to sample and process the received waveform at very high rates (at least to 100 MHz and likely to 1 GHz or higher). HTSC materials allow for very fast response in appropriately configured circuits and could easily meet these electronic warfare requirements.

Electronic warfare systems also measure threat transmitter center frequency as well as spectral characteristics over the transmit bandwidth. A relatively broadband receiver coverage over the entire expected threat band (as in surveillance) is desirable, as is a very precise and stable frequency selectivity for threat characterization and recognition. Having both characteristics implies a large number of frequency resolution cells. Such a capability might be exploited in electronic warfare signal processing using matched filtering or angle-of-arrival estimation. Again HTSC-based devices may provide improved performance because their lower losses translate into sharper frequency

response filter characteristics and thus more frequency resolution cells per bandwidth, and their lower noise translates into lower noise sources (local oscillators) and lower phase-noise measurement (for angle measurement based on phase measurement).

When considering applications of HTSC technology to electronic warfare I focus primarily on low-power rather than high-power systems. Hence the primary type of equipment considered will be electronic warfare receivers (e.g., radar, radar warning, radar homing, ECM, ESM, and electronic intelligence receivers). Rather than examine the requirements for each system, I will consider the generic requirements for all systems.

The important system parameters are:

- Frequency coverage and resolution
- Amplitude dynamic range and sensitivity
- Time-of-arrival resolution
- Angle-of-arrival resolution
- Polarization

For frequency coverage any band between 3 MHz and 100 GHz should be considered, although the obvious threat bands for adversary systems generally lie below 18 GHz and are usually restricted to appropriate atmospheric transmission bands. If laser systems are used, as they might be for blinding FPA's, then the frequencies of interest would be much higher (in the 30-500-THz range). Bandwidths can be anything the mission requires; the key parameter is the number of frequency cells of interest (and hence, frequency measurement accuracy) over a given instantaneous bandwidth. It is often desirable that this number be large (1000 or more). Pulse characteristics required are driven more exclusively by the particular threat (e.g., rise time, etc.) that it can support. Pulse widths in the 10-100-ns range and rise times in the 1-10-ns range must be processed for receiving and reconstructing short-pulse radar signals. Dynamic range is set by a number of factors, including signal environment (single versus multitone) and individual component linearity and system noise. Generally 70 dB is the minimum desirable for processing, such as high-quality spectral analysis. Pulse amplitudes must be detected in the presence of noise to achieve long-range intercept. Hence sensitivities must be very good, on the order of -120 dBm or better. Time-of-arrival accuracy will be set by the sampling rate that can be achieved. For conventional systems the best real time (single shot) is in the 1-10-ns range. Angle-of-arrival accuracy depends on the method used, for example, amplitude versus phase comparison, Doppler frequency, microwave lens, etc. Achieving an angular accuracy of 1 in 1000 over a fairly narrow percentage bandwidth (e.g., 3 %) would be useful. A requirement on polarization angle resolution, which is the ability to detect small polarization components orthogonal to the principal com-

ponent, is in the range of 1-2 degrees. State-of-the-art conventional systems will be limited in most of the above characteristics to the values indicated.

Figure 21 shows an architecture for a generic electronic warfare system.⁸⁷ Here the basic subsystems are identified, and most are potential candidates for the insertion of HTSC technology because the expected performance gain may be very significant. For all subsystems the additional cost of HTSC insertion will come primarily from the use of cryogenics. One advantage of HTSC devices, however, is that the cryogenics will likely use liquid nitrogen, which is much cheaper and easier to store and maintain than liquid helium. (The relative cost of using liquid nitrogen over liquid helium was discussed earlier in section 3.1.) One of the system trade-offs lies between HTSC-based system performance gain versus cryogenics/packaging cost.

A generic electro-optical receiver system can be viewed as a series of subsystems comprising a detector or detector array, readout circuits, preamplifier, and signal processor, as illustrated in Fig. 22. The most likely application of HTSC devices would be for detectors, readout interconnects, and signal processors. It is much less likely that a purely superconducting preamplifier will be devised.

The key system characteristics for electro-optical applications, particularly single and multiple detectors, are

- Spectral bandwidth
- Noise equivalent power (or detectivity)
- Response time
- Spatial resolution

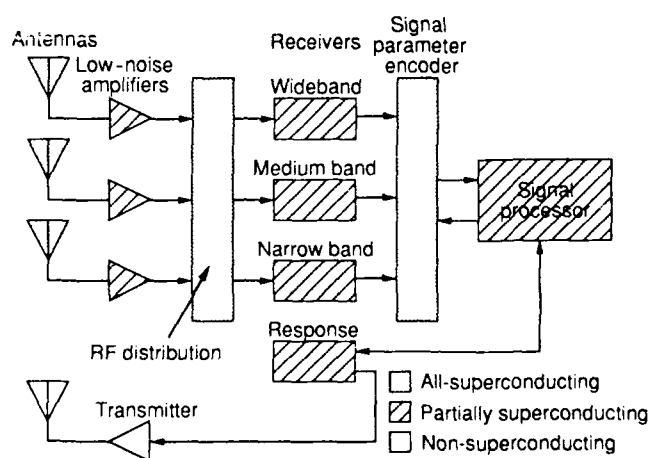


Figure 21 Architecture for a generic electronic warfare system.

⁸⁷ E. C. Niehenke, "Innovative Microwave Design Leads to Smart, Small EW Systems," *Microwave J.* **31**, 28 (1988).

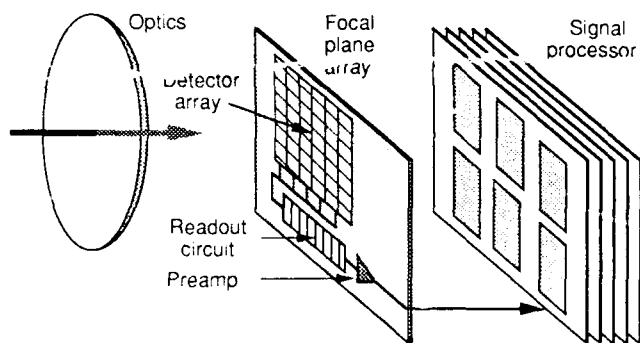


Figure 22 Basic elements of a generic focal plane array.

The requirements for spectral bandwidth are clearly delineated in Fig. 23, which shows the spectral content of typical targets or sources. The atmospheric transmission curve, including the 3-5- μm and 8-12- μm bands, is shown below these characteristics.

The requirements for noise equivalent power (NEP) and response time (τ) are plotted together, as shown in Fig. 24, since they are tied together by the relationship

$$NEP \cdot \tau = \text{constant} \quad (15)$$

for type-II detectors (e.g., bolometers, for which $\tau = \tau_{th}$). Equation 15 is an important trade-off for applications. For comparison, some examples of bolometer measurements are included in this figure.^{58,88-97} Several regions of NEP

versus response time are shown for various technologies and applications. Note that the requirements for simple acquisition and tracking (irrespective of intrinsic target contrast) fall in the range of $\tau = 1 \text{ ms}$ to 1 s , and $NEP \leq 10^{-8} \text{ W/Hz}^{1/2}$. Imaging would require faster response (i.e., on the order of $\tau = 200 \text{ ns}$ for a single pixel dwell time) and equal or better sensitivity (NEP). The far-IR astronomy sensitivity requirement is probably beyond the

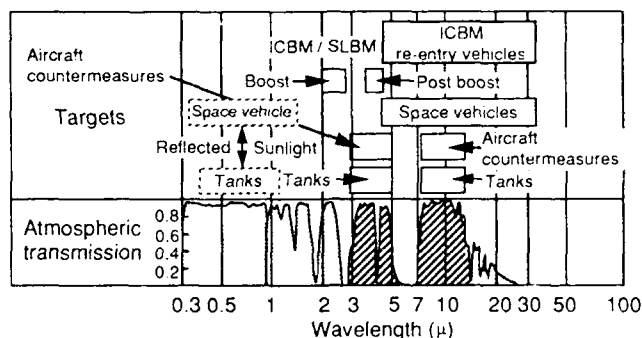


Figure 23 Spectral range of typical targets and atmospheric transmission function over visible and infrared bands.

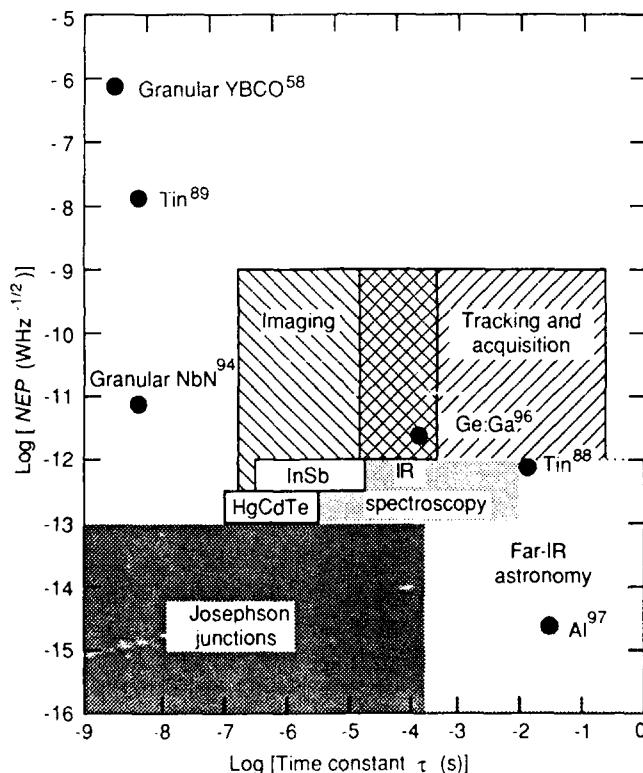


Figure 24 Summary of prior art in bolometers and comparison to typical application requirements.

⁵⁸D. H. Martin and D. Bloor, "The Application of Superconductivity to the Detection of Radiant Energy," *Cryogenics*, 159-165 (Mar 1961).

⁵⁹C. L. Bertin and K. Rose, "Radiant-Energy Detection by Superconducting Films," *J. Appl. Phys.* **39**, 2561 (1968).

⁶⁰C. L. Bertin and K. Rose, "Comparison of Superconducting and Semiconducting Bolometers," *J. Appl. Phys.* **42**, 163 (1971).

⁶¹R. M. Katz and K. Rose, "Comparative Studies of Noise Limitations in Superconducting Thin-Film Radiation Detectors," *Proc. IEEE* **61**, 55 (1973).

⁶²J. Clarke, G. I. Hoffer, P. L. Richards, and N.-H. Yeh, "Superconductive Bolometers for Submillimeter Wavelengths," *J. Appl. Phys.* **48**, 4865 (1977).

⁶³K. Rose, "Superconductive FIR Detectors," *IEEE Trans. Electron. Devices* **27**, 118 (1980).

⁶⁴S. A. Wolf, U. Strom, J. C. Culbertson, and D. Paget, "Superconducting Granular NbN Bolometer for Ultrafast Spectroscopy," *IEEE Trans. Magn.* **21**, 920 (1985).

⁶⁵M. Leung, U. Strom, J. C. Culbertson, J. H. Claassen, S. A. Wolf, and R. W. Simon, "NbN/BN Granular Films—A Sensitive, High-Speed Detector for Pulsed Far-Infrared Radiation," *Appl. Phys. Lett.* **50**, 1691 (1987).

⁶⁶E. I. Low, *JOSA* **51**, 1300 (1961).

⁶⁷J. Clarke, G. I. Hoffer, P. L. Richards, and N.-H. Yeh, *Low Temperature Physics—LT14*, Vol. 4, M. Krusius and M. Vuorio, eds., Elsevier, New York, pp. 226-229 (1975).

scope of HTSC-based bolometric detectors but within the reach of properly designed Josephson (SIS-type) detectors. Fourier transform spectroscopy may be a realizable area of application.

Spatial resolution is set by optical system design (i.e., instantaneous field-of-view [IFOV], number of pixels, signal processing bandwidth) and should not be a problem, since these parameters are largely unaffected by the use of superconductors.

4.2 PROJECTED PERFORMANCE GAINS

Which system requirements can be improved by using HTSC technology? The answer depends on the particular component types used. (For instance, angle-of-arrival estimation may be implemented via phase comparison monopulse or a microwave lens. Both methods require phase delay, but one will use a lumped-element single-channel phase shifter while the other will use a multichannel network of delay lines of varying length.) Rather than trying to establish the relationship between a given system requirement and a given component performance in this report (which is a longer-term R&D objective), consider just the important electronic warfare component characteristics in general that may be improved through the use of HTSC materials:

- Losses
- Noise sensitivity
- Frequency
- Bandwidth
- Response time

Losses can be improved at low frequencies better than at high frequencies because the conductivity of superconducting materials is a complex quantity that decreases with increasing frequency. At microwave frequencies the effective surface resistance (R_s) is key. The R_s is estimated to be 10–100 times smaller for HTSC materials than for normal metals when operating below the superconducting gap frequency and at low reduced temperature (≤ 0.1 K). This value of R_s is still relatively high compared to that for conventional superconductors and may be due to the granularity and anisotropy of the so-called dirty ceramic materials.⁹³ Lower R_s translates directly into correspondingly lower attenuation per unit length in microstriplines, higher Q factors for resonators, and sharper skirts for bandpass filters. Lower losses can also allow greater densification of integrated circuits. Greater packing density is achieved because, with lower microstrip conductor losses, smaller strip widths and thinner dielectrics can be used (while still maintaining the correct impedance levels for signal propagation and without introducing more cross talk).

Typical circuit area reductions are ~ 400 , given strip width reductions of ~ 20 .⁷ Lower losses also mean less power dissipation when, for instance, Josephson junctions are used as switches in such circuits.

Noise sensitivity can be improved over conventional devices when using Josephson-junction-based devices such as microwave and millimeter-wave detectors as well as SQUID's. (The difficulties inherent in the fabrication of Josephson junctions, however, are of significant concern.) There will be some degradation in noise sensitivity for HTSC devices expected at 77 K over comparable devices using conventional superconductors at low temperatures (4.2 K). For instance, DC SQUID's have a noise energy that varies linearly with temperature, so that the noise should be greater by a factor of 13 dB at 77 K (versus 4.2 K). The only other parameter that can be used to ameliorate this is the size of the SQUID, which is subject to design. For wideband video detection of microwave or millimeter-wave radiation the detector sensitivity varies as the square root of temperature. Then the degradation should be only about 7 dB. For narrowband heterodyne detection (in which either a Josephson junction or external source could be used as the local oscillator), the degradation is comparable to the DC SQUID device. These projections are theoretical, but the baseline for comparison is derived from conventional superconducting devices, which make up the lowest noise devices in electronics. Consider, for example, the SIS mixer; it has a 4-dB-lower noise figure than can be achieved with Schottky barrier diodes at room temperature.⁹⁸ This reduction can be directly translated into 4-dB-less size for the receiving antenna for a given performance. Thus reduced noise can affect overall antenna (and hence package) size.

Although noise degradation at 77 K versus 4.2 K is not catastrophic, further investigation is warranted to find the means to use HTSC materials and still achieve optimal device sensitivity at the appropriate operating temperature and device size. Noise sensitivity is also affected by how HTSC devices are constructed and interfaced with amplifying circuits. Moreover, nonthermal noise such as $1/f$ noise, which is caused partly by the granular nature of the HTSC materials, must be understood and controlled. Interface to amplifying circuits *in situ* (on-chip, with proper impedance matching and temperature control) is essential.

Frequency of operation of HTSC devices is limited intrinsically to values less than the superconducting energy-gap frequency, ν_g , which at temperatures low compared to T_c is quite high. For example, ν_g at $T = 0$ is approximately 7 THz for HTSC materials. These HTSC-based devices may be operated up to nearly the gap frequency

⁹⁸P. H. Carr, "Potential Microwave Applications of High Temperature Superconductors," *Microwave J.* 30, 91–93 (1987).

before substantial losses begin to occur. Since the energy gap decreases as the temperature approaches T_c , it is desirable to operate at a fraction of T_c (e.g., $\leq 0.7 T_c$) to achieve the best performance. Depending on the application, the effective bandwidth will also be roughly set by the gap frequency value. Other factors such as parasitic electrical and thermal time constants will affect actual device bandwidth, but these parameters are subject to design.

Conventional superconducting circuits have achieved response times on the order of tens of picoseconds, and there is no reason to expect that HTSC-based circuits could not switch just as rapidly. Thus for sampling or A/D conversion the concomitant aperture time can be just as short. This should lead to very fast analog-signal-processing circuits (as well as digital circuits), provided parasitic effects can be obviated. That is, individual HTSC devices may also be limited in their signal response time because of the particular configuration used as well as materials-related characteristics. For example, if a resistive transition switch is used, the response time is set by the thermal time constant of a narrow strip of HTSC material and the associated thermal impedance of the superconductor/substrate combination. Conversely, a tunnel junction may have its response time set by its intrinsic parasitic time constant, which may be much less. If, however, the parasitic capacitance can be tuned out with other capacitance or inductance, the response should become intrinsic and go inversely as Δ (i.e., $\tau \sim h/\Delta$), which should be the shortest of all time constants. If response time depends only on the gap frequency, it will be very short, on the order of 0.2 ps for isolated HTSC devices.

4.3 CANDIDATE SUBSYSTEMS FOR HTSC INSERTION

Referring to Figs. 21 and 22, several categories of RF or electro-optical applications matched to the various subsystems of generic electronic warfare or electro-optical systems can be delineated. Electronic warfare subsystems include antennas, transmission-line devices, receivers, and signal processors; electro-optical subsystems include detectors (single, linear, or FPA), free-space matching networks, and signal processors.

For electronic warfare applications electrically small antennas, superdirective arrays, and microwave lenses are potential candidates for HTSC insertion. Transmission-line devices include resonators, cavities, filters, and low-loss transmission lines as well as signal delay lines, phase shifters, and circulators. The likeliest form that most of these components will take using HTSC devices will be microstrip because it is so convenient to fabricate and so compact for packaging and cooling. Other components im-

portant in receivers include preamplifiers, oscillators, mixers, and detectors. Lower noise figure preamplifiers can be achieved with HTSC interconnects than with conventional interconnects, as explained in section 3.1. Very stable local oscillators for accurate frequency reference could be made using HTSC resonators and Josephson junctions. Josephson junctions could also be used as mixers and detectors and would provide excellent sensitivity and very broad bandwidth. For signal processing some important components include chip interconnects, sampling devices for A/D conversion, and dispersive analog delay lines. (Note that many of the potential applications of HTSC technology have already been tried with niobium as the superconductor.)

For antenna subsystems the integration of an antenna with a detector and preamplifier (i.e., the receiver) in close proximity is very desirable. The entire system could be made of HTSC material except for the preamplifier, which could be a GaAs-MESFET-type amplifier. If made sufficiently small, the entire assembly could be cooled easily with small-scale cryogenics. Another example by which a small low-impedance superconducting detector could be interfaced to free space is illustrated in Fig. 25.^{99,100} A "vee"-shaped impedance transformer matches a bolometer to free space. This design is especially appropriate for millimeter- and submillimeter-wave receivers, so that quasi-optical components, including lenses for collimation, can be used.

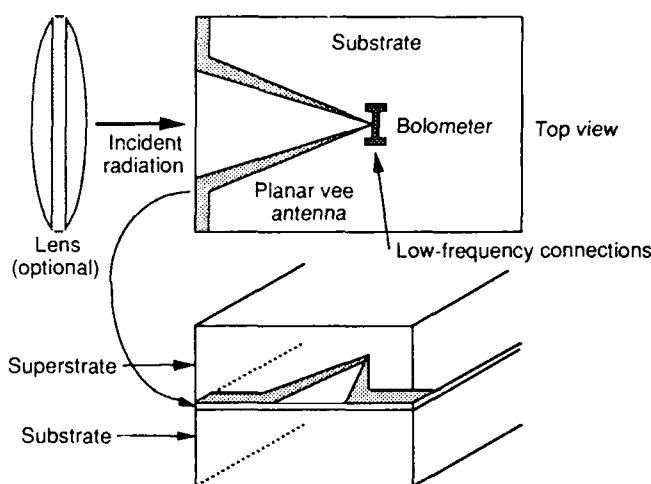


Figure 25 Quasi-optical impedance matching "vee" antenna for a possible HTSC bolometer.

⁹⁹K. E. Irwin, T. Van Duzer, and S. E. Schwarz, "A Planar Antenna-Coupled Superconductor-Insulator-Superconductor Detector," *IEEE Trans. Magn.* **21**, 216 (1985).

¹⁰⁰T.-L. Huang, D. B. Rutledge, and S. E. Schwarz, "Planar Sandwich Antennas for Submillimeter Applications," *Appl. Phys. Lett.* **34**, 9 (1979).

Some examples of microstrip transmission-line components¹⁰¹ that could be made out of HTSC materials are illustrated in Fig. 26. These and other components can be evaluated by their performance relative to conventional devices at the appropriate operating temperature. It is expected that some of these components would be used as part of a larger integrated circuit such as the oscillator illustrated in Fig. 27. This circuit would consist of a nar-

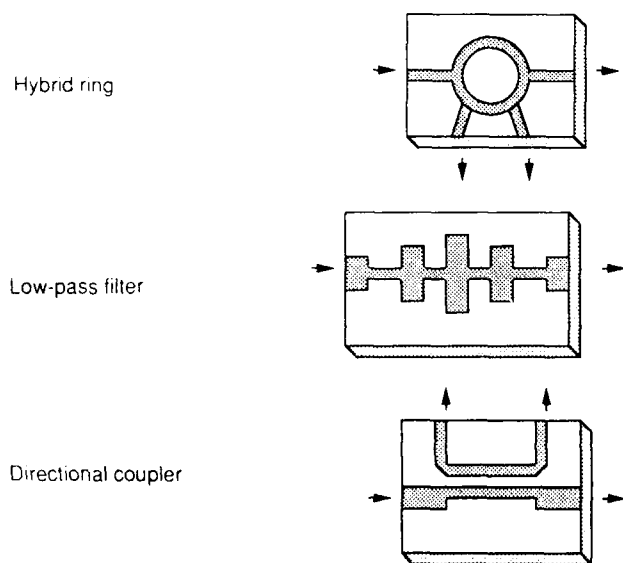


Figure 26 Some possible HTSC microstripline components.

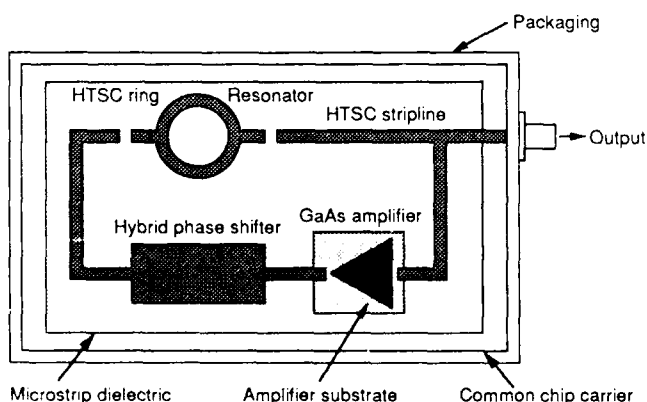


Figure 27 Integrated circuit microstrip oscillator using feedback coupling, consisting of an HTSC ring resonator, HTSC interconnects, hybrid phase shifter, and GaAs amplifier on a common chip.

¹⁰¹ R. K. Hoffman, *Handbook of Microwave Integrated Circuits*, Artech House, Norwood, Mass. (1987).

rowband (high- Q) resonator, feedback-coupled through a semiconducting (probably GaAs MESFET) amplifier and hybrid (superconducting/semiconducting) phase shifter (which might consist of semiconducting diodes and superconducting circulators). Since the GaAs MESFET would have a lower noise figure using superconducting gate electrodes and since the superconducting resonator would have a higher Q than a conventional resonator, the overall benefit should be an oscillator with lower noise and narrower bandwidth than conventional oscillators designed the same way.

Mixers and detectors made from Josephson junctions or hybrid combinations of HTSC materials with other materials are feasible if some materials and materials-processing problems can be solved. Investigators are hopeful that novel solutions will be found to develop such nonlinear HTSC devices. If Josephson junctions can be made, then very stable frequency-selective low-noise oscillators can be built. In addition, very-low-noise fast-responding detectors and mixers may be achieved at 77 K.

To produce maximum sensitivity for detection (and mixing) Josephson junctions are desirable. To make them with HTSC materials will require extremely fine control of the fabrication process, since the coherence length (ξ_0) at temperatures low compared to T_c is very short (≈ 2 nm or less in the plane of the deposited film and ≈ 0.4 nm perpendicular to it) and gets shorter as it approaches T_c . Weakening of the superconducting state must occur only over a distance of $\approx \xi_0$ in a superconducting weak link to achieve the desired ideal Josephson effect.

Some examples of potential HTSC-based Josephson junctions were illustrated in Fig. 5. In a tunnel junction the interface between the two superconducting sides may have to be extremely small since the coherence length perpendicular to the plane is so short (≈ 0.4 nm). Further, the control of the interfacial layer thickness may be difficult. If a microbridge geometry is devised, possible ways of weakening it might include ion implantation or laser pyrolysis, which have already been successfully tried, or controlling the grain size and grain boundaries to achieve a controlled critical path through the microbridge. This concept is illustrated in Fig. 28. Here there might be one or more such paths created, and the serial/parallel collection of such Josephson-junction intergrain couplings might behave as a coherent (or at least partially coherent) array with higher dynamic range than a single weak link.

4.4 IMPLEMENTATION AND INTEGRATION ISSUES

Key areas of investigation regarding HTSC implementation and integration, which are common to some of the

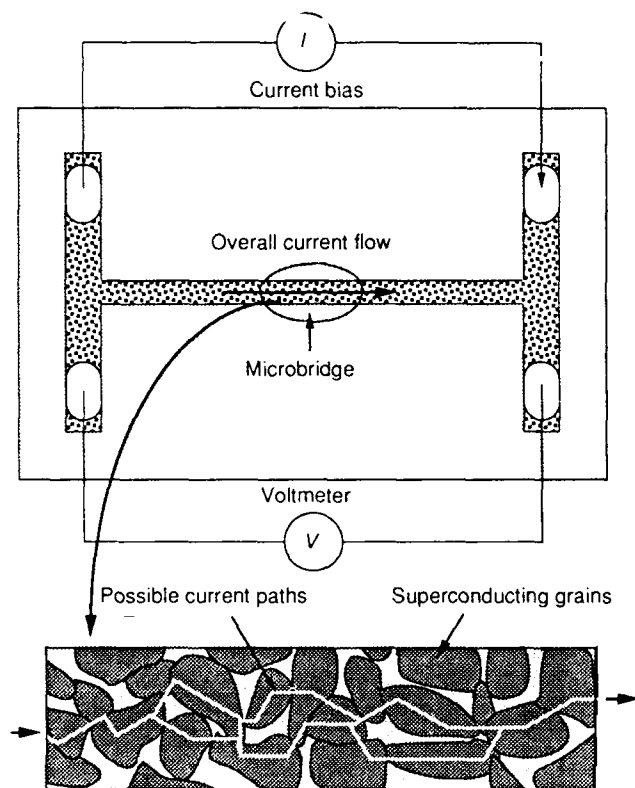


Figure 28 Typical circuit configuration and mesoscopic detail of a grain-boundary array-type HTSC microbridge.

electronic warfare and electro-optical subsystems and components described above, are

- Fabrication of HTSC devices on technologically useful substrates
- Physical parameters of HTSC materials
- Single-chip integration
- Total subsystem cryogenic cooling

Extensive materials-science-oriented characterization of multilayered HTSC structures is needed before practical applications can be developed. All the applications require the integration of superconductors with one or more materials that include insulators, semiconductors, and metals. Thus interfacial effects are of crucial importance. The constraints imposed by mismatch of lattice constants between the superconducting material and the substrate and the inevitable diffusion between the two materials must be considered. The appropriate use of thin buffer layers to reduce strains as well as interdiffusion should be probed. Thin passivation layers may also be important to guard the physical and chemical stability of thin-film-layered structures. Reducing the operating temperature for forming and processing multilayered structures will be helpful

in decreasing the interdiffusion and consequent degradation of superconducting films. The details are the subject of further research, however; a survey and assessment of deposition and patterning techniques, as well as related materials selection criteria are the subject of a separate report.¹⁰²

Critical currents $\leq 10^6$ A/cm² have already been achieved in HTSC thin films, but these highly desirable values are seen only in films deposited on oriented crystals of strontium titanate, zirconium oxide, and magnesium oxide. Whether equally high values can be achieved for HTSC films on technologically useful substrates (such as quartz, silicon, GaAs), with or without buffer layers, remains to be seen. The low sensitivity of the critical current to externally applied magnetic fields is another essential feature that needs further exploration. The problem of critical currents in superconducting ceramics is further complicated by the inherent high anisotropy of these materials, and it would be necessary to determine if properly oriented superconducting films are going to be absolutely essential in exploiting high-temperature superconductors in applications.¹⁰³

An important parameter for technological applications of superconductors is the ratio, κ , of the London penetration depth, λ_L , and the coherence length, ξ_0 (i.e., λ_L / ξ_0). The most desired values of κ are best exhibited by the conventional superconductor, niobium. The higher values of κ in superconducting ceramics resulting from much-reduced values of ξ_0 (0.4–2 nm, depending on orientation) might hamper the technological usefulness of these materials. Small values of ξ_0 undoubtedly pose challenges for fabrication of active devices based on Josephson junctions; however, the granular nature of superconducting oxides might allow the exploitation of intrinsic Josephson junctions that are prevalent in these materials, as described previously.

To achieve the maximum benefit from using HTSC materials it will probably be necessary to fully integrate all components of a given subsystem on a single substrate. This and the need to operate at higher frequencies will force the use of all-superconducting (or at least partially-superconducting) VHSIC or MIMIC circuits. This integration process will be reasonably straightforward for passive components, but for active devices either semiconducting and/or superconducting nonlinear devices (such as Josephson junctions) must be considered. An active element may take the form of an amplifier, oscillator, or mix-

¹⁰² R. M. Sova, "Assessment of High Temperature Superconducting Device Fabrication Techniques," JHU/APL Technical Memorandum (to be published, 1990).

¹⁰³ B. G. Boone and K. Moorjani, "Superconducting Devices for Electronic Warfare Systems," JHU/APL Proposal Submitted to Air Force Office of Scientific Research, AD-12395 (Jul 1988).

er of some kind. For semiconducting amplifiers, we must address the superconductor/semiconductor interface problem, which has two aspects: fabricating such an interface and avoiding the creation of spurious diode characteristics at the interface that foil the proper use of the semiconducting amplifier. During the fabrication process postdeposition annealing of the HTSC material requires high temperatures that would destroy a previously fabricated semiconducting amplifier. Either the superconductor must be deposited first, or annealing temperatures should be lowered. In addition, buffer layers should be used to inhibit diffusion at the semi/superconducting interface. These considerations will force the creation of entirely new design rules.

An important issue of implementation is to integrate conventional preamplifiers with superconducting circuits on common chip carriers (hybrid circuits) as an interim solution to achieving a high signal-to-noise ratio. Understanding the operation of cold electronics, particularly MOSFET's (metal oxide semiconductor field-effect transistors) and GaAs MESFET's at 77 K,¹⁰⁴ and using them in specific low- and high-frequency applications (respectively), such as bolometric detection¹⁰⁵ and high-speed signal processing circuits, are critical tasks.

The integration of HTSC-based components in electronic warfare and electro-optical systems will probably require the cooling of entire subsystems to make efficient use of the cryogenics needed while maintaining compactness. Fortunately the cryogenics community has developed a considerable technology base over the past few years for supporting liquid-nitrogen-range (77-K) cryogenics for small-scale airborne systems, especially electro-optical sensors such as HgCdTe FPA's. Nevertheless these cryogenic systems will have to be adapted and possibly expanded to accommodate new HTSC-based devices, such as entire antenna and stripline assemblies, preamplifier modules, and receiver packages.

Some examples of small-scale cryocoolers are the microminiature refrigerator (MMR, Inc.) originated by Little,¹⁰⁶ which is illustrated in Fig. 29. This device uses the Joule-Thompson effect (in a special capillary design in sapphire to cool an input gas such as nitrogen) to achieve an operating temperature of ~ 80 K in a single-stage implementation. A typical cryogenic cooler for IR detectors,

designed at APL,¹⁰⁷ is illustrated in Fig. 30. This design was intended to cool an IR detector for missile guidance. A third example of a miniature closed-cycle cryocooler (manufactured by International Cryogenics Enterprises) is shown in Fig. 31. It uses a Stirling cycle for high efficiency and reliability to meet the requirements of cooling IR FPA's down to 77 K for such systems as common-module forward-looking IR systems.¹⁰⁸

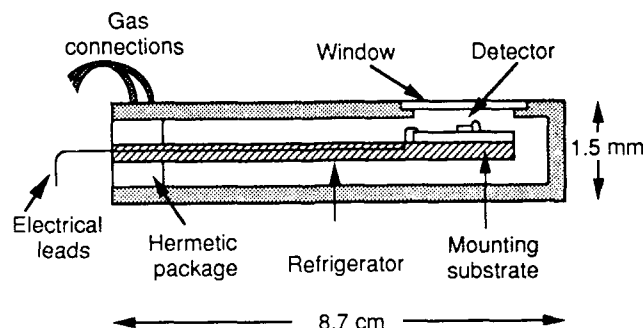


Figure 29 Microminiature refrigerator using capillary Joule-Thompson cooler etched in sapphire substrate.

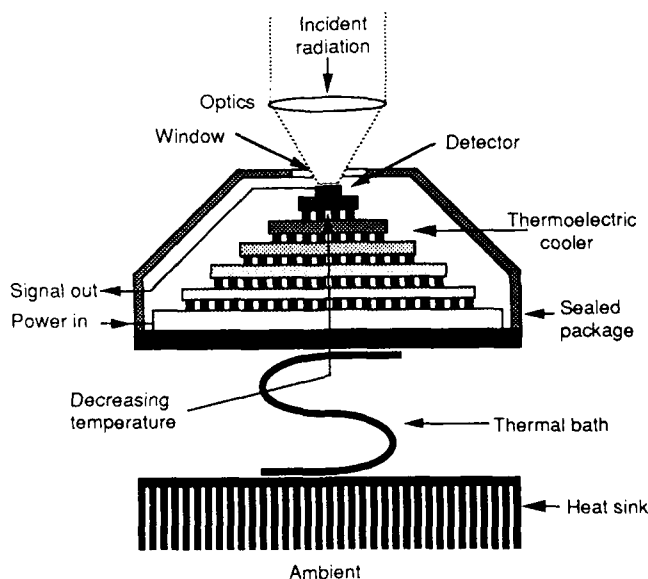


Figure 30 Small-scale Joule-Thompson cooler for missile-guidance applications.

¹⁰⁴C.A. Liechti and R. B. Larrick, "Performance of GaAs MESFET's at Low Temperatures," *IEEE Trans. Microwave Theory Tech.* **24**, 376 (1976).

¹⁰⁵J. H. Goedel, "Liquid-Helium-Cooled MOSFET Preamplifier for Use with Astronomical Bolometer," *Rev. Sci. Instrum.* **48**, 389 (1977).

¹⁰⁶W. A. Little, "Design and Construction of Microminiature Cryogenic Refrigerators," in *Future Trends in Superconductive Electronics*, AIP Conf. Proc. **44**, B. S. Deaver, Jr., C. M. Falco, J. H. Harris, and S. A. Wolf, eds., pp. 421-424 (1978).

¹⁰⁷T. P. Carey, "Preliminary Design Review of IR Dome and Window Seeker Configurations," JHU/APL Technical Memorandum TCE-87-77 (3 Apr 1987).

¹⁰⁸M. Kushnir and C. S. Naiman, "Integrated Cooler/Dewar Structures for Detector Array Cooling in Infrared Systems," *Cryocoolers 5 Conf.*, Monterey, Calif. (18-19 Aug 1988).



Figure 31 Closed-cycle (Stirling) cryocooler for IR focal plane arrays (adapted from Ref. 108).

To illustrate the insertion of HTSC components into conventional systems I highlight two examples below. In one, a typical monopulse radar system shown in Fig. 32, the input RF filter can be made of HTSC material and would afford the receiver higher Q and hence better frequency selectivity. One or two orders-of-magnitude increase in Q would be of interest. In addition, lower-noise, higher- Q oscillators could be used in the radar-receiver chain, if constructed from HTSC materials. Performance would be enhanced if surface resistance can, in fact, be made less than the surface resistance of ordinary copper at reduced temperatures (≤ 77 K). Another example, shown in Fig. 33, is a passive ESM receiver in which the instantaneous frequency measurement of received emissions is determined using correlation. Correlation at RF (or intermediate fre-

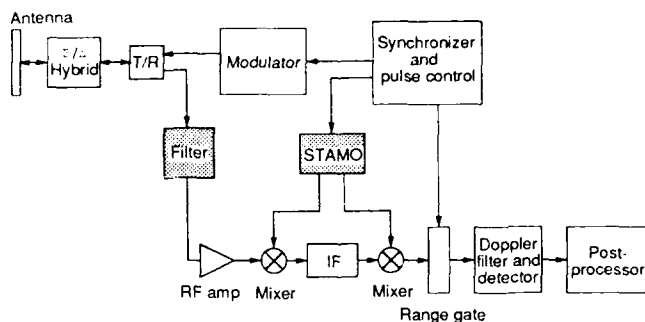


Figure 32 Typical monopulse radar block diagram showing possible HTSC device insertion points. (STAMO = STable Master Oscillator.)

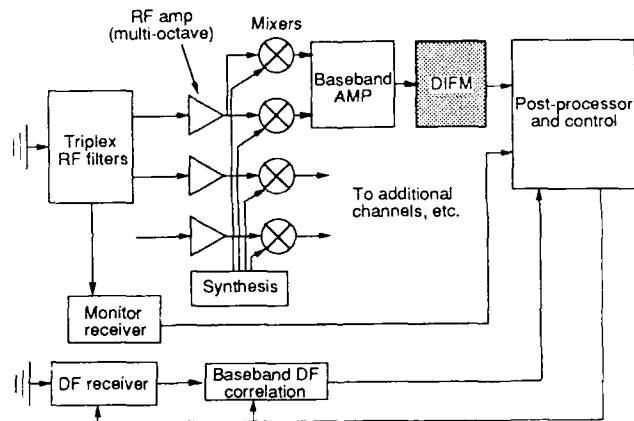


Figure 33 Typical ESM block diagram showing possible HTSC device insertion point. (DIFM = differential instantaneous frequency measurement.)

quency) could be implemented with superconducting delay lines. Fixed-delay (slow-wave) devices could be used to achieve stable but controllable delays for phase measurement and subsequent frequency measurement in microstrip technology. Both examples, however, point to the need for building compact cryocoolers to effectively insert HTSC technology into conventional systems.

5.0 CONCLUSIONS AND FUTURE CONSIDERATIONS

A technology assessment such as described in this report is necessarily incomplete and tentative because the successful use of HTSC technology depends not only on technical progress in one area of application, but on technical progress in other areas as well as economic incentives. The question is not just a matter of "if" but also "when." The author's purpose has been to juxtapose the basic technology next to relevant system application areas and thereby see where promising HTSC devices, perhaps even novel designs, emerge. If HTSC technology is to become practical such an assessment at an even more detailed level will be required. Before detailed system insertion assessments can be addressed, however, feasibility demonstrations and critical experiments must be conducted in the laboratory. The initial assessment provided in this report should help guide the choice of experiments. Many investigators appear to be interested in the same devices and acknowledge the same key issues.

The most promising thin-film devices are

- Bolometers
- Nonequilibrium granular-array detectors
- SQUID's
- Tunnel junctions or similar devices
- Microstrip slow-wave delay lines
- Microstrip resonators
- High-speed interconnects

Many other devices (not treated in this report) such as larger-scale microwave components (e.g., antennas, entire stripline assemblies) also appear to be promising. Some key issues for thin-film-device development and applications are:

- Tailoring grain-size distribution and controlling mesoscopic film geometry to make controlled granular arrays
- Controlling film defects to make good tunnel junctions and control flux-flow
- Perfecting passivation and buffer layers to enable the use of technologically useful substrates and to effectively interface with semiconductor circuits
- Reducing microstrip device losses by minimizing RF surface resistance through improved film morphology
- Using substrates with low dielectric loss and anisotropy that lattice-match to HTSC materials for making microstrip devices
- Integrating HTSC devices into hybrid integrated circuits with conventional cold electronics
- Inserting hybrid cold electronics packages into larger systems with efficient, small-scale cryocooler technology

To achieve the successful development of HTSC devices some basic goals for materials scientists and fabrication engineers must be met:

- Grow epitaxial films to optimize superconducting-state parameters (T_c , H_c , J_c).
- Control surface morphology and stoichiometry for multilayers.
- Lower processing temperatures to enable compatibility with semiconductor circuits.

Prospects for near-optimal electronic applications will depend on the technologist's ability to fabricate layered epitaxial nanostructures with high-quality surfaces and interfaces. Only then can development focus on practical devices with significant performance gains over conventional devices. Ultimately a mix of HTSC, LTSC, conventional semiconductor, and opto-electronic technologies will be employed.

Once initial feasibility demonstrations and critical experiments are accomplished and the technology matures, specific system requirements should be addressed to match components to actual applications. The best way to foster research and development activities for such purposes is first to establish centers of excellence for materials processing and device fabrication.¹⁰⁹ Investigators from university, industrial, and government laboratories could then send in specific designs for processing. Once the components are built investigators could test and evaluate them. Visiting scientist and engineer programs should also be established at such facilities. After the feasibility of specific devices is thus demonstrated, larger program initiatives should be sponsored, such as the DARPA Terahertz Imaging Radar Initiative.

Since system laboratories such as APL are well versed in application needs in electro-optics and electronic warfare, it makes sense that component feasibility demonstration experiments, as well as technology insertion assessments, should be conducted there. This is currently underway at APL, and all critical tasks are being carried out: materials science research, device design, fabrication, test and evaluation, system assessment, and requirements definition. Because the materials processing and device fabrication problems with HTSC materials are so much greater than those with LTSC materials, APL is focusing its greatest efforts in that area.

¹⁰⁹K. Moorjani, "DoD Superconducting Electronic Facility," attachment to correspondence to Executive Officer, Organizing Committee, Superconducting Electronics Fabrication Facility (15 Sep 1988).

REFERENCES

- ¹J. R. Wilson, "U.S. Navy Plans and Programs for Superconducting R&D," Proc. of the Conference on Superconductivity R&D in the U.S. Navy, NSWC, White Oak, Md. (9-10 Feb 1988).
- ²J. R. Cauffman, "Office of Naval Technology (ONT) Exploratory Development Program (6.2) in Superconductivity," Proc. of the Conference on Superconductivity R&D in the U.S. Navy, NSWC, White Oak, Md. (9-10 Feb 1988).
- ³J. J. Suter and A. G. Bates, "Ultra-Stable Time and Frequency Device for Tactical Aircraft Radar," JHU/APL SDO 8446 (Apr 1987).
- ⁴A. J. DiNardo, J. G. Smith, and F. R. Adams, "Superconducting Microstrip High-Q Microwave Resonators," *J. Appl. Phys.* **42**, 186 (1971).
- ⁵R. S. Withers, A. C. Anderson, J. B. Green, and S. A. Reible, "Superconductive Delay-Line Technology and Applications," *IEEE Trans. Magn.* **21**, 186 (1985).
- ⁶S. R. Stein and J. P. Turneare, "Superconducting Resonators: High Stability Oscillators and Applications to Fundamental Physics and Metrology," in *Future Trends in Superconductive Electronics*, AIP Conf. Proc. #44, B. S. Deaver, Jr., C. M. Falco, J. H. Harris, and S. A. Wolf, eds., pp. 192-213 (1978).
- ⁷R. L. Kautz, "Miniaturization of Normal-State and Superconducting Striplines," *J. Res. Nat. Bur. Stand.* **84**, 247 (1979).
- ⁸J. L. Abita, "Superconductive Electrode Semiconductor Components," JHU/APL TEO-87-072 (20 Apr 1987).
- ⁹R. J. Dinger, "NCS Panel on High Frequency Applications," Proc. of the Conference on Superconductivity R&D in the U.S. Navy, NSWC, White Oak, Md. (9-10 Feb 1988).
- ¹⁰M. Nisenoff, "Naval Consortium on Superconductivity, Panel on Infrared Sensor Systems," Proc. of the Conference on Superconductivity R&D in the U.S. Navy, NSWC, White Oak, Md. (9-10 Feb 1988).
- ¹¹K. Moorjani, F. J. Adrian, B. F. Kim, J. Bohandy, T. E. Phillips, W. J. Green, E. Agostinelli, and B. G. Boone, "High Temperature Superconducting Thin Films," *Johns Hopkins APL Tech. Dig.* **9**, 174 (1988).
- ¹²W. Meissner and R. Ochensfeldt, "Ein Neuer Effekt bei Eintritt der Supraleitfähigkeit," *Naturwiss.* **21**, 787 (1933).
- ¹³J. Bardeen, L. N. Cooper, and J. R. Schrieffer, "Theory of Superconductivity," *Phys. Rev.* **108**, 1175 (1957).
- ¹⁴B. S. Deaver, Jr., and W. M. Fairbank, "Experimental Evidence for Quantized Flux in Superconducting Cylinders," *Phys. Rev. Lett.* **7**, 43 (1961).
- ¹⁵R. Doll and M. Nabauer, "Experimental Proof of Magnetic Flux Quantization in a Superconducting Ring," *Phys. Rev. Lett.* **7**, 51 (1961).
- ¹⁶B. D. Josephson, "Possible New Effects in Superconductive Tunneling," *Phys. Lett.* **1**, 251 (1962).
- ¹⁷P. W. Anderson and J. M. Rowell, "Probable Observation of the Josephson Superconducting Tunneling Effect," *Phys. Rev. Lett.* **10**, 230 (1963).
- ¹⁸M. Tinkham, "Junctions—Types, Properties, and Limitations," in *Future Trends in Superconductive Electronics*, AIP Conf. Proc. #44, B. S. Deaver, Jr., C. M. Falco, J. H. Harris, and S. A. Wolf, eds., pp. 269-279 (1978).
- ¹⁹A. Barone and G. Paterno, "Voltage Current Characteristics," in *Physics and Application of the Josephson Effect*, John Wiley & Sons, pp. 122-136 (1982).
- ²⁰F. Y. Fradin, "DOE Programs for Large Scale Applications," Superconductivity Seminar, Wash., D.C. (20 Nov 1987).
- ²¹R. T. Kampwirth, J. H. Kang, and K. E. Gray, "Superconducting Properties of Magnetron Sputtered Bi-Sr-Ca-Cu-O and Tl-Ba-Ca-Cu-O Thin Films," in *Science and Technology of Thin Film Superconductors*, R. D. McConnell and S. A. Wolf, eds., Plenum Press, pp. 165-173 (1988).
- ²²C. J. Gorter and H. B. G. Casimir, "On Supraconductivity I," *Physica* **1**, 306 (1934).
- ²³F. London and H. London, "The Electromagnetic Equations of the Superconductors," *Proc. Roy. Soc. A* **149**, 71 (1935a).
- ²⁴D. C. Mattis and J. Bardeen, "Theory of Anomalous Skin Effect in Normal and Superconducting Metals," *Phys. Rev.* **111**, 412 (1958).
- ²⁵J. Clarke, "Small-Scale Analog Applications of High-Transition-Temperature Superconductors," *Nature* **333**, 29 (1988).
- ²⁶A. P. Malozemoff, "Computer Applications of High Temperature Superconductivity," *Physica C* **153-155**, 1049 (1988).
- ²⁷Y. G. Vendik and A. B. Kozyrev, "Superconducting Films in Microwave Electronics (Survey)," *Izv. Vyssh. Uchebn. Zaved. Radioelektron.* **26**, 18 (1983).
- ²⁸N. K. Welker and F. D. Bedard, "Digital Josephson Technology—Present and Future," in *Future Trends in Superconductive Electronics*, AIP Conf. Proc. #44, B. S. Deaver, Jr., C. M. Falco, J. H. Harris, and S. A. Wolf, eds., pp. 425-436 (1978).
- ²⁹T. Van Duzer and C. W. Turner, *Principles of Super-*

conductive Devices and Circuits, Elsevier North Holland (1981).

- ³⁰L. Solymar, "Current-Voltage Characteristics," in *Superconductive Tunneling and Applications*, Wiley-Interscience, pp. 165-185 (1972).
- ³¹J. Clarke in *Superconductor Applications: SQUID's and Machines*, B. B. Schwartz and S. Foner, eds., Plenum, N.Y. (1977).
- ³²"A Practical Way to Turn Out Josephson Junction Chips," *Electronics* **60**, 49-56 (1987).
- ³³S. K. Pan, A. R. Kerr, M. J. Feldman, and A. W. Kleinsasser, "SIS Technology Boosts Sensitivity of MM-Wave Receivers," *Microwave RF*, 139 (Sep 1988).
- ³⁴A. Landrie, "Superconducting IC's Generate and Detect Signals to 100 GHz," *Microwave RF*, 163-164 (Sep 1988).
- ³⁵R. E. Harris and C. A. Hamilton, "Fast Superconducting Instruments," in *Future Trends in Superconductive Electronics*, AIP Conf. Proc. #44, B. S. Deaver, Jr., C. M. Falco, J. H. Harris, and S. A. Wolf, eds., pp. 448-458 (1978).
- ³⁶J. Clarke, "Low-Frequency Applications of Superconducting Quantum Interference Devices," *Proc. IEEE* **61**, 8 (1973).
- ³⁷R. A. Davidheiser, "Superconducting Microstrip Filters," in *Future Trends in Superconductive Electronics*, AIP Conf. Proc. #44, B. S. Deaver, Jr., C. M. Falco, J. H. Harris, and S. A. Wolf, eds., pp. 219-222 (1978).
- ³⁸R. Davidheiser, "Frequency Stable Sources Using Superconducting Microstrip Resonators," Proc. 34th Annual Frequency Control Symposium, USAERADCOM, Ft. Monmouth, N.J. (May 1980).
- ³⁹R. S. Withers, A. C. Anderson, P. V. Wright, and S. A. Reible, "Superconductive Tapped Delay Lines for Microwave Analog Signal Processing," *IEEE Trans. Magn.* **19**, 480 (1983).
- ⁴⁰J. T. Lynch, R. S. Withers, A. C. Anderson, P. V. Wright, and S. A. Reible, "Multigigahertz-Bandwidth Linear-Frequency-Modulated Filters Using a Superconductive Stripline," *Appl. Phys. Lett.* **43**, 319 (1983).
- ⁴¹R. W. Ralston, "Signal Processing: Opportunities for Superconducting Circuits," *IEEE Trans. Magn.* **21**, 181 (1985).
- ⁴²S. A. Reible, A. C. Anderson, P. V. Wright, R. S. Withers, and R. W. Ralston, "Superconductive Convolver," *IEEE Trans. Magn.* **19**, 475 (1983).
- ⁴³S. A. Reible, "Superconductive Convolver with Junction Ring Mixers," *IEEE Trans. Magn.* **21**, 193 (1985).
- ⁴⁴R. Meservey and P. M. Tedrow, "Measurements of the Kinetic Inductance of Superconducting Linear Structures," *J. Appl. Phys.* **40**, 2028 (1969).
- ⁴⁵J. M. Pond, J. H. Claassen, and W. L. Carter, "Kinetic Inductance Microstrip Delay Lines," *IEEE Trans. Magn.* **23**, 903 (1987).
- ⁴⁶J. M. Pond, J. H. Claassen, and W. L. Carter, "Measurements and Modeling of Kinetic Inductance Microstrip Delay Lines," *IEEE Trans. Microwave Theory Tech.* **35**, 1256 (1987).
- ⁴⁷D. A. Gandolfo, A. Boornard, and L. C. Morris, "Superconductive Microwave Meander Lines," *J. Appl. Phys.* **39**, 2657 (1968).
- ⁴⁸P. V. Mason and R. W. Gould, "Slow-Wave Structures Utilizing Superconducting Thin-Film Transmission Lines," *J. Appl. Phys.* **40**, 2039 (1969).
- ⁴⁹J. M. Pond and C. M. Krowne, "Slow-Wave Properties of Superconducting Microstrip Transmission Lines," *IEEE MTT-S Dig.* **1**, 449 (1988).
- ⁵⁰S. Baliga, M. Radparvar, and S. M. Faris, "The Superconducting Phase Shifter in the Development of a Terahertz Imaging Radar System," RADC-TR-87-157, Final Tech. Rep. (Oct 1987).
- ⁵¹S. M. Faris, "Generation and Measurement of Ultrashort Current Pulses with Josephson Devices," *Appl. Phys. Lett.* **36**, 1005 (1980).
- ⁵²R. L. Kautz, "Picosecond Pulses on Superconducting Striplines," *J. Appl. Phys.* **49**, 308 (1978).
- ⁵³R. Sobolewski, C. V. Stancampiano, G. Mourou, and D. Butler, "Picosecond Pulse Generation Capability of Optically Driven Superconducting Thin Films," *Phys. Status Solidi* **83**, K203 (1984).
- ⁵⁴C. C. Chi, W. J. Gallagher, I. N. Duling, III, D. Grischowsky, N. J. Halas, M. B. Ketchen, and A. W. Kleinsasser, "Subpicosecond Optoelectronic Study of Superconducting Transmission Lines," *IEEE Trans. Magn.* **23**, 1666 (1987).
- ⁵⁵N. E. Glass and D. Rogovin, "Optical Control of Microwave Propagation in Superconducting Devices," *Appl. Phys. Lett.* **54**, 182 (1989).
- ⁵⁶C. A. Hamilton, F. L. Lloyd, and R. L. Kautz, "Superconducting A/D Converter Using Latching Comparators," *IEEE Trans. Magn.* **21**, 197 (1985).
- ⁵⁷"PSP-1000 Picosecond Signal Processor," Hypres, Inc., product brochure (Sep 1986).
- ⁵⁸M. Leung, P. R. Broussard, J. H. Claassen, M. Osofsky, S. A. Wolf, and U. Strom, "Optical Detection in Thin Granular Films of Y-Ba-Cu-O at Temperatures between 4.2 and 100 K," *Appl. Phys. Lett.* **51**, 2046 (1987).
- ⁵⁹M. G. Forrester, M. Gottlieb, J. R. Gavalier, and A. I. Braginski, "Optical Response of Epitaxial Films of YBa₂Cu₃O_{7-x}," *Appl. Phys. Lett.* **53**, 1332 (1988).
- ⁶⁰H. J. Goldsmid, K. K. Gopinathan, D. N. Matthews, K. N. R. Taylor, and C. A. Baird, "High-T_c Superconductors as Passive Thermo-Elements," *J. Phys. D: Appl. Phys.* **21**, 344 (1988).

- ⁶¹Y. Enomoto, T. Murakami, and M. Suzuki, "Infrared Optical Detector Using Superconducting Oxide Thin Film," *Physica C* **153-155**, 1592 (1988).
- ⁶²P. L. Richards, J. Clarke, R. Leoni, P. Lerch, S. Verhese, M. R. Beasley, T. H. Gabelle, R. H. Hammond, R. Rosenthal, and S. R. Spielman, "Feasibility of the High T_c Superconducting Bolometer," *Appl. Phys. Lett.* **54**, 283 (1989).
- ⁶³A. Fathy, D. Kalokitis, and E. Belohoubek, "Microwave Characteristics and Characterization of High T_c Superconductors," *Microwave J.* **31**, 75-94 (Oct 1988).
- ⁶⁴W. L. Olson, M. Eddy, T. W. James, McD. Robinson, D. D. P. Casavant, E. J. Smith, A. Cardona, and R. B. Hammond, "Low Surface Resistance Thin Films of $Tl_2Ca_2Ba_2Cu_3O_{10}$ Produced by Chemical Deposition and Laser Ablation," Workshop on High Temperature Superconductivity, Huntsville, Ala. (23-25 May 1989).
- ⁶⁵D.-H. Wu, W. L. Kennedy, C. Zahopoulos, and S. Sridhar, "Characteristics and Growth of Single Crystals of $Y_1Ba_2Cu_3O_{7-x}$ with Superior Microwave Properties," *Appl. Phys.* **55**, 696 (1989).
- ⁶⁶J. Konopka, R. Sobolewski, A. Konopka, and S. J. Lewandowski, "Microwave Detection and Mixing in Y-Ba-Cu-O Thin Films at Liquid-Nitrogen Temperatures," *Appl. Phys. Lett.* **53**, 796 (1988).
- ⁶⁷J. Moreland, L. F. Goodrich, J. W. Ekin, T. E. Capobianco, A. F. Clark, A. I. Braginski, and A. J. Panson, "Josephson Effect above 77 K in a YBaCuO Break Junction," *Appl. Phys. Lett.* **51**, 540 (1987).
- ⁶⁸T. Yamashita, A. Kawakami, S. Noge, W. Xu, M. Takada, T. Komatsu, and K. Matusita, "Josephson Effects at 77 K in Grain Boundary Bridge Made of Thick Films," *Jap. J. Appl. Phys.* **27**, L1107 (1988).
- ⁶⁹M. G. Blamire, G. W. Morris, R. E. Somekh, and J. E. Evetts, "Fabrication and Properties of Superconducting Device Structures in $YBa_2Cu_3O_{7-x}$ Thin Films," *J. Phys. D: Appl. Phys.* **20**, 1330 (1987).
- ⁷⁰G. C. Hilton, E. B. Harris, and D. J. Van Harlingen, "Growth, Patterning, and Weak-Link Fabrication of Superconducting $YBa_2Cu_3O_{7-x}$ Thin Films," *Appl. Phys. Lett.* **53**, 1107 (1988).
- ⁷¹P. England, T. Venkatesan, X. D. Wu, A. Inam, M. S. Hegde, T. L. Cheeks, and H. G. Craighead, "Intrinsic Superconductor/Normal-Metal/Superconductor-like Weak Links in $Y_1Ba_2Cu_3O_{7-x}$ Thin Films," *Appl. Phys. Lett.* **53**, 2336 (1988).
- ⁷²Y. Enomoto and T. Murakami, "Infrared Optical Detectors Using BPB Films," *Rev. Elec. Commun. Lab.* (NTT, Japan) **34**, 263 (1986).
- ⁷³Y. Enomoto and T. Murakami, "Optical Detector Using Superconducting $BaPb_{0.1}Bi_{0.9}O_3$ Thin Films," *J. Appl. Phys.* **59**, 3807 (1986).
- ⁷⁴T. Murakami, M. Suzuki, and K. Moriwaki, "Some Phenomena in a Boundary Josephson Junction (BPB) Array," *Rev. Elec. Commun. Lab.* (NTT, Japan) **34**, 257 (1986).
- ⁷⁵M. Suzuki, T. Murakami, and Y. Enomoto, "Boundary Josephson Junctions in $BaPb_{1-x}Bi_xO_3$ (BPB) Polycrystalline Film," *Rev. Elec. Commun. Lab.* (NTT, Japan) **34**, 249 (1986).
- ⁷⁶J. Takada, T. Terashima, Y. Bando, H. Mazaki, K. Iijima, K. Yamamoto, and K. Hirata, "Tunnel Junctions Using Oxide Superconducting Thin Films Epitaxially Grown on $SrTiO_3$," *Appl. Phys. Lett.* **53**, 2689 (1988).
- ⁷⁷R. H. Koch, C. P. Umbach, M. M. Opreysko, J. D. Mannhart, B. Bumble, G. J. Clark, W. J. Gallagher, A. Gupta, A. Kleinhasser, R. B. Laibowitz, R. B. Sandstrom, and M. R. Scheuermann, "DC SQUID's Made from $YBa_2Cu_3O_7$," *Physica C* **153-155**, 1615 (1988).
- ⁷⁸C. M. Pegrum, G. B. Donaldson, A. H. Carr, and A. Hendry, "Observation of Quantum Interference Effects and SQUID Operation in a Bulk Sample of $YBa_2Cu_3O_7$ at 77 K and 4.2 K," *Appl. Phys. Lett.* **51**, 1364 (1987).
- ⁷⁹C. E. Gough, "Flux Quantization and SQUID Magnetometry Using Ceramic Superconductors," *Physica C* **153-155**, 1569 (1988).
- ⁸⁰U. Kawabe, "Application of High-Temperature Superconductors to SQUID's and Other Devices," *Physica C* **153-155**, 1586 (1988).
- ⁸¹I. S. Gergis, J. A. Titus, P. H. Kobrin, and A. B. Harker, "Planar Weak-Link Devices from YBaCuO and BiSrCaCuO Films," *Appl. Phys. Lett.* **53**, 2226 (1988).
- ⁸²L. A. Hornak, S. K. Tewksbury, and M. Hatamian, "The Impact of High- T_c Superconductivity on System Communications," in *Proc. 38th Electronic Components Conf.*, pp. 152-158 (9-11 May 1988).
- ⁸³T. L. Hylton, A. Kapitulnik, M. R. Beasley, J. P. Carini, L. Drabeck, and G. Gruner, "Weakly Coupled Grain Model of High-Frequency Losses in High T_c Superconducting Thin Films," *Appl. Phys. Lett.* **53**, 1343 (1988).
- ⁸⁴J. P. Carini, A. M. Awasthi, W. Beyermann, G. Gruner, T. Hylton, K. Char, M. R. Beasley, and A. Kapitulnik, "Millimeter-Wave Surface Resistance Measurements in Highly Oriented $YBa_2Cu_3O_{7-x}$ Thin Films," *Phys. Rev. B* **37**, 9726 (1988).
- ⁸⁵C. J. Lobb, "What Can (and Can't) Be Measured in Superconducting Networks," *Physica B* **152**, 1 (1988).
- ⁸⁶M. A. H. Nerenberg, J. H. Beasley, and J. A. Blackburn, "Chaotic Behavior in an Array of Coupled

- Josephson Weak Links," *Phys. Rev. B.* **36**, 8333 (1987).
- ⁸⁷E. C. Niehenke, "Innovative Microwave Design Leads to Smart, Small EW Systems," *Microwave J.* **31**, 28 (1988).
- ⁸⁸D. H. Martin and D. Bloor, "The Application of Superconductivity to the Detection of Radiant Energy," *Cryogenics*, 159-165 (Mar 1961).
- ⁸⁹C. L. Bertin and K. Rose, "Radiant-Energy Detection by Superconducting Films," *J. Appl. Phys.* **39**, 2561 (1968).
- ⁹⁰C. L. Bertin and K. Rose, "Comparison of Superconducting and Semiconducting Bolometers," *J. Appl. Phys.* **42**, 163 (1971).
- ⁹¹R. M. Katz and K. Rose, "Comparative Studies of Noise Limitations in Superconducting Thin-Film Radiation Detectors," *Proc. IEEE* **61**, 55 (1973).
- ⁹²J. Clarke, G. I. Hoffer, P. L. Richards, and N.-H. Yeh, "Superconductive Bolometers for Submillimeter Wavelengths," *J. Appl. Phys.* **48**, 4865 (1977).
- ⁹³K. Rose, "Superconductive FIR Detectors," *IEEE Trans. Electron. Devices* **27**, 118 (1980).
- ⁹⁴S. A. Wolf, U. Strom, J. C. Culbertson, and D. Paget, "Superconducting Granular NbN Bolometer for Ultrafast Spectroscopy," *IEEE Trans. Magn.* **21**, 920 (1985).
- ⁹⁵M. Leung, U. Strom, J. C. Culbertson, J. H. Claassen, S. A. Wolf, and R. W. Simon, "NbN/BN Granular Films—A Sensitive, High-Speed Detector for Pulsed Far-Infrared Radiation," *Appl. Phys. Lett.* **50**, 1691 (1987).
- ⁹⁶F. J. Low, *JOSA* **51**, 1300 (1961).
- ⁹⁷J. Clarke, G. I. Hoffer, P. L. Richards, and N.-H. Yeh, *Low Temperature Physics-LT14*, Vol. 4, M. Krusius and M. Vuorio, eds., Elsevier, New York, pp.226-229 (1975).
- ⁹⁸P. H. Carr, "Potential Microwave Applications of High Temperature Superconductors," *Microwave J.* **30**, 91-93 (1987).
- ⁹⁹K. E. Irwin, T. Van Duzer, and S. E. Schwarz, "A Planar Antenna-Coupled Superconductor-Insulator-Superconductor Detector," *IEEE Trans. Magn.* **21**, 216 (1985).
- ¹⁰⁰T.-L. Huang, D. B. Rutledge, and S. E. Schwarz, "Planar Sandwich Antennas for Submillimeter Applications," *Appl. Phys. Lett.* **34**, 9 (1979).
- ¹⁰¹R. K. Hoffman, *Handbook of Microwave Integrated Circuits*, Artech House, Norwood, Mass. (1987).
- ¹⁰²R. M. Sova, "Assessment of High Temperature Superconducting Device Fabrication Techniques," JHU/APL Technical Memorandum (to be published, 1990).
- ¹⁰³B. G. Boone and K. Moorjani, "Superconducting Devices for Electronic Warfare Systems," JHU/APL Proposal Submitted to Air Force Office of Scientific Research, AD-12395 (Jul 1988).
- ¹⁰⁴C.A. Liechti and R. B. Larrick, "Performance of GaAs MESFET's at Low Temperatures," *IEEE Trans. Microwave Theory Tech.* **24**, 376 (1976).
- ¹⁰⁵J. H. Goedel, "Liquid-Helium-Cooled MOSFET Preamplifier for Use with Astronomical Bolometer," *Rev. Sci. Instrum.* **48**, 389 (1977).
- ¹⁰⁶W. A. Little, "Design and Construction of Microminiature Cryogenic Refrigerators," in *Future Trends in Superconductive Electronics*, AIP Conf. Proc. #44, B. S. Deaver, Jr., C. M. Falco, J. H. Harris, and S. A. Wolf., eds., pp. 421-424 (1978).
- ¹⁰⁷T. P. Carey, "Preliminary Design Review of IR Dome and Window Seeker Configurations," JHU/APL Technical Memorandum TCE-87-77 (3 Apr 1987).
- ¹⁰⁸M. Kushnir and C. S. Naiman, "Integrated Cooler/Dewar Structures for Detector Array Cooling in Infrared Systems," *Cryocoolers 5 Conf.*, Monterey, Calif. (18-19 Aug 1988).
- ¹⁰⁹K. Moorjani, "DoD Superconducting Electronics Facility," attachment to correspondence to Executive Officer, Organizing Committee, Superconducting Electronics Fabrication Facility (15 Sep 1988).

GLOSSARY

Symbol	Definition	Units
A	Cross-sectional area of superconductor	cm^2
D^*	Detectivity	$\text{cm Hz}^{-1/2} \text{W}^{-1}$
e	Electron charge (1.6×10^{-19})	c
e^*	Effective Cooper pair charge ($\sim 2e$)	c
\mathbf{E}	Electric field vector	V cm^{-1}
h	Planck's constant (6.62×10^{-27})	erg s
H_c	Critical field	A m
I	Current	A
I_b	Current bias	A
I_c	Critical current	A
I_p	Pulse current	A
$I_s(t)$	Signal current	A
I_{th}	Threshold current	A
J	Current density	A m^{-2}
\mathbf{J}	Current density vector	A m^{-2}
J_c	Critical current density	A m^{-2}
k_B	Boltzmann constant (1.38×10^{-16})	erg K^{-1}
L_{eff}	Effective inductance of superconductor	H
L_J	Phase-dependent (Josephson) equivalent inductance	H
m	Mass of electron	gm
m^*	Effective mass of Cooper pair ($\sim 2m$)	gm
n	Total number of current carriers	
n_p	Number of pairs	
n_q	Number of quasiparticles	
NEP	Noise equivalent power	$\text{W Hz}^{-1/2}$
R_s	Surface resistance	$\Omega \text{ sq}^{-1}$
$R_0(\omega)$	Residual surface resistance	$\Omega \text{ sq}^{-1}$
T	Absolute temperature	K
T_c	Transition temperature	K
v_F	Fermi velocity	cm s^{-1}
V	Voltage across Josephson junction	V
Z_0	Characteristic impedance	Ω
$\Delta(T)$	Superconducting energy gap	meV
$\Delta\phi$	Phase difference across Josephson junction	rad
κ	Ratio of London penetration depth to coherence length	
$\lambda_L(T)$	London penetration depth	nm
μ_0	Magnetic permeability of free space (1.26×10^{-6})	$\text{Wb A}^{-1} \text{m}^{-1}$
ν_g	Superconducting energy-gap frequency	Hz
π	Pi (3.14159)	
Ψ	Superconducting macroscopic wave function	
ϕ	Superconducting phase	
σ	Conductivity	$\Omega^{-1} \text{cm}^{-1}$
σ_1	Real (resistive) part of superconductor conductivity	$\Omega^{-1} \text{cm}^{-1}$
σ_2	Imaginary (reactive) part of superconductor conductivity	$\Omega^{-1} \text{cm}^{-1}$
ξ_0	Coherence length at $T = 0$	nm
Φ	Magnetic flux	$\text{Wb (T m}^2\text{)}$

Φ_0	Magnetic flux quantum	$Wb (T m^2)$
τ	Relaxation time of normal electron velocity; detector response time constant	s
τ_g	Gate delay in superconducting sampler	s
τ_{th}	Thermal time constant of bolometer	s
ω	Radian frequency	$rad s^{-1}$

INITIAL DISTRIBUTION EXTERNAL TO THE APPLIED PHYSICS LABORATORY*

The work reported in TG 1377 was done under Navy Contract N00039-89-C-5301 and is related to Task X9B1XXXX, supported by SPAWAR.

ORGANIZATION	LOCATION	ATTENTION	No. of Copies
DEPARTMENT OF DEFENSE			
Defense Advanced Research Projects Agency	Arlington, VA 22209	Accessions	1
Defense Technical Information Center	Alexandria, VA 22314	Accessions	12
DEPARTMENT OF THE NAVY			
SPAWAR	Arlington, VA 20363-5100	Library	1
NAVPRO	Laurel, MD 20707		1
NAVAIRSYSCOM	Washington, DC 22202	Library, AIR 7226	2
Naval Weapons Center	China Lake, CA 93555	R. J. Dinger, 3814	1
Naval Research Laboratory	Washington, DC 20375-5000	M. Nisenoff, 6854	1
Naval Air Development Center	Warminster, PA 18974-5000	R. M. Williams, 505A	1
Office of the Chief of Naval Research	Arlington, VA 22217-5000		1
Office of Naval Technology	Arlington, VA 22203		1
DEPARTMENT OF THE AIR FORCE			
AFOSR	Wright-Patterson AFB, OH 45433-6503	P. Ryan	1
MISCELLANEOUS			
University of Virginia	Charlottesville, VA 22901	B. S. Deaver	1
Wilkes College	Wilkes-Barre, PA	A. Razavi	1

Requests for copies of this report from DoD activities and contractors should be directed to DTIC, Cameron Station, Alexandria, Virginia 22314 using DTIC Form 1 and, if necessary, DTIC Form 55.

*Initial distribution of this document within the Applied Physics Laboratory has been made in accordance with a list on file in the APL Technical Publications Group.