SUPERCONDUCTING MICROWAVE TECHNOLOGY

Superconductivity is a remarkable state of matter in which electric current can flow inside materials without any detectable resistance. This phenomenon was discovered by the Dutch physicist H. K. Onnes in 1911. While studying the temperature dependence of the electric resistance of mercury in his newly invented helium liquefier, Onnes found that below a temperature of about 4 K, the resistance abruptly fell to below measurable limits.

In a superconductor, perfect electric conductivity or zero resistivity occurs only below a "critical temperature" T_C. This happens because the electric current, instead of being carried by single electrons, is carried by pairs of electrons called Cooper pairs which have the ability to conserve energy because of quantum mechanical reasons. A direct current induced in a superconducting ring has been shown to persist for over two years without any measurable decay. From this type of experiment the upper limit on resistivity ρ is $\sim 10^{-25}\ \Omega \cdot \mathrm{m}$. Since ρ for copper is $\sim 10^{-8}\ \Omega \cdot \mathrm{m}$, a factor of 10^{17} larger, it is believed that the electric resistance of a superconductor is truly zero.

Another important characteristic of superconductors was the discovery by W. Meissner and R. Ochsenfeld in 1933 that a superconductor expels all magnetic flux from its interior; that is, a superconductor is also a perfect diamagnet. This phenomenon is known as the Meissner effect.

A key area of technological applications of superconductors is in high-frequency devices, particularly at frequencies in the radio-wave, microwave, and millimeter-wave spectral ranges. Broadly speaking, two principal areas of high-frequency applications can be identified:

- *Passive devices,* typically using resonant and transmission line structures, exploiting the low loss properties of superconductors.
- *Active elements,* such as oscillators, mixers, logic elements, and other similar devices, which exploit a macroscopic quantum coherence property of the charge carriers, called the Josephson effect.

The price to pay to achieve the superior performance is the need to cool the superconducting device to temperatures well below room temperature. This means the use of cryogenic fluids like liquid nitrogen or liquid helium, or a mechanical cryocooler. Despite the need for a cryogenic environment, there are many applications where the superior performance of superconductors prevails over conventional devices.

SUPERCONDUCTING MATERIALS

Superconductivity has been observed in diverse types of materials including pure metals, alloys, semimetals, organic materials, semiconductors, polymers, and even elemental insulators. Presently, at least 26 of the naturally occurring elements are known to be superconducting at sufficiently low temperatures at ambient pressure, and the number of alloys and intermetallic compounds are well above 1000.

A significant advancement in understanding superconductivity was the theory of Bardeen, Cooper, and Schrieffer in 1957. This theory successfully described the microscopic mechanism of superconductivity and explained the properties of most superconductors for nearly 30 years.

Then came the era of high-temperature superconductivity, with the groundbreaking discovery by Bednorz and Müller in 1986 of superconductivity in a Ba–La–Cu–O compound with T_C around 30 K, which subsequently earned them a Nobel Prize. This discovery rekindled the interest in superconductivity and spurred the hopes of finding new technological applications. The efforts led to the discovery of other copper–oxide-based superconductors that have critical temperatures well in excess of the boiling point of nitrogen (77 K), an easily available and cheap cryogenic fluid usable for commercial applications. Presently the highest critical temperature is about 150 K at high pressures in $HgBa_2Ca_2Cu_3O_8$.

Superconductors fall in two broad categories, namely, "high critical temperature" (or "high-T_C") and "low critical temperature" (or "low-T_C") materials. (There are many other ways of classifying them, such as Type I and Type II superconductors, heavy fermion and conventional superconductors, and so on.) Some examples of low-T_C superconductors, particularly relevant to commercial applications, are niobium and its alloys, such as NbN and Nb_3Ge. These have critical temperatures in the region of 10 K to 20 K. The high-T_C superconductors that are most commonly used include $YBa_2Cu_3O_7$ (commonly referred to as YBCO or Y-123, T_C ~93 K), $Bi_2Sr_2CaCu_2O_8$ (commonly referred to as BSCCO or Bi-2212, T_C ~90 K), and $Tl_2Ba_2Ca_2Cu_3O_{10}$ (TBCCO or Tl-2223, T_C ~125 K).

Besides the critical temperature, some other relevant physical parameters that characterize a superconductor are as follows:

- *The London penetration depth* (λ_L): The depth to which an applied direct current (dc) magnetic field is confined because of the Meissner effect.
- *The coherence length* (ξ): The length scale over which the two electrons forming the Cooper pairs are separated.
- *The (thermodynamic) critical field* (H_C): The magnetic field whose associated free energy is equal to the free energy change in the superconducting transition. A "Type I" superconductor will completely expel the applied field below H_C and will become normal abruptly as the applied field exceeds this magnitude, assuming no demagnetization effects. For "Type II" superconductors (which includes practically all of the superconductors of technological interest), the field starts to penetrate in the form of vortices at a "lower critical field" H_{C1} ($<H_C$), but superconductivity is not quenched until the applied field exceeds the "upper critical field" H_{C2} ($>H_C$).

Some superconductors of relevance to microwave applications are described in Table 1 along with their relevant properties (λ_L, ξ, H_{C1}, and H_{C2} quoted are extrapolated to $T = 0$ K).

Substrates for Thin-Film Superconductors

For most electronic applications, including microwave devices, superconductors are necessarily used in the form of thin films. This requires the use of a foreign material for a substrate. Some of the popular substrates include sapphire (α-Al_2O_3), lanthanum aluminate ($LaAlO_3$), and magnesium oxide (MgO). Ferroelectric substrates like strontium titanate

Table 1. Some Commercially Used Superconducting Materials and Their Physical Properties

Material	T_C (K)	λ_L (nm)	ξ (nm)	H_{C1} (Oe)	H_{C2} (Oe)	Crystal Structure
Pb	7.2	37	83	803	803	Face-centered cubic
Nb	9.2	32	39	~1600	~3200	Body-centered cubic
NbN	16	50	4	300		B1
Nb_3Ge	23.2				3.6×10^{5}[a]	A15
YBCO[b]	93	140	~2	200	~10^6	Orthorhombic
TBCCO[b]	127	220[c]	2.6[c]			Tetragonal
BSCCO[b]	~90	500	0.16			Tetragonal

[a] At 4.2 K.
[b] YBCO, TBCCO, BSCCO, and most other high-T_C superconductors are highly anisotropic. The values given are for microwave current flowing in the *ab*-plane, which is often the plane of epitaxial growth and the desired geometry in most technological applications.
[c] Average of *ab*-plane and *c*-axis value.

($SrTiO_3$) and $KTa_{1-x}Nb_xO_3$ are also used to achieve tunability at the expense of additional dielectric loss.

The electrical parameters that characterize the properties of a substrate material are its dielectric constant ϵ and its loss tangent tan δ. (The loss tangent of a substrate is defined as $\tan \delta = \sigma/\omega\epsilon$, where σ is the conductivity.) Other factors such as environmental stability, mechanical strength, chemical inertness, and absence of magnetic moment are also important. Close lattice match between the deposited film and the substrate is essential to achieve good epitaxial growth. These parameters have been measured and investigated by various researchers using different techniques for most substrate materials.

In general, the dielectric constant would be more or less frequency independent unless the frequency is close to a resonance frequency of the material. The dielectric constant is also expected to have a weak temperature dependence for nonferroelectric substances. The loss tangent is expected to increase with temperature. Table 2 provides the most commonly accepted values of these material parameters for some of the substrates, measured at 10 GHz and 77 K unless otherwise stated.

Most of these materials have high ϵ; this imposes certain restrictions, especially for high-frequency applications. A high ϵ reduces the dimension of the device and thus imposes stringent dimensional tolerance, especially in the millimeter-wave region. But consideration of dielectric constant has to be sacrificed for some even more important parameters, namely, a lattice match between the substrate and the film, and not widely different thermal expansivity from the superconductor. A lattice mismatch would create atomic level strain and leads to poor superconducting properties. Another criterion is that losses in the substrate must be negligible compared to the losses in the superconductor. Heavy twinning in materials like $LaAlO_3$ creates problems in multilayer films. When the substrate is reheated for the deposition of a new layer, the thermally induced movement of the twin boundaries strain the previously deposited layers.

There are numerous methods of depositing superconducting films on substrates, the most common being pulsed laser deposition (PLD), coevaporation, and off-axis sputtering or physical vapor deposition (PVD). Each of these methods has its pros and cons. For example, PLD produces high-quality films at a fast rate (a few angstroms per second) but only over relatively small areas, typically less than 2 in. diameter. The PVD method is useful for producing larger area films, but the deposition rate is only a fraction of an angstrom per second. Another method of film deposition, namely, metal-organic chemical vapor deposition (MOCVD), popular in the semiconductor industry, has also been tried for high-T_C superconductors, although somewhat less successfully owing to the chemical and structural complexity of the high-T_C materials. We refer the reader interested in deposition technique to some useful resources (see, for example, Ref. 1).

The "quality" of a deposited superconducting film is characterized by several parameters, such as the critical temperature T_C, the transition width ΔT_C, and the critical current density J_C, which is the maximum lossless current per unit cross-sectional area that the film can carry. The higher the T_C and J_C and the lower the ΔT_C, the better the film.

THE SUPERCONDUCTOR–MICROWAVE INTERACTION

A superconductor has zero electrical resistance only at zero frequency (dc). At any finite frequency, it exhibits losses that

Table 2. Some Commonly Used Substrate Materials for Superconducting Thin-Film Devices

Material	Dielectric Constant	Loss Tangent	Crystal Structure	Growth Surface	Remarks
$LaAlO_3$	25	5×10^{-6}	Rhombohedral	(110)	Usually twinned
$YAlO_3$	16	10^{-5}	Orthorhombic	(110)	
MgO	9.65	6.2×10^{-6}	Cubic	(100)	Good lattice match
Sapphire	8.6	3.8×10^{-8}	Hexagonal	(11 02)	Very low loss
$NdGaO_3$	23	3.2×10^{-4}	Orthorhombic	(110)	Good for multilayer circuits
$SrTiO_3$	300	3×10^{-4}	Cubic	(100)	Good for tunable device applications
YSZ	27	7.4×10^{-4}	Cubic	(100)	

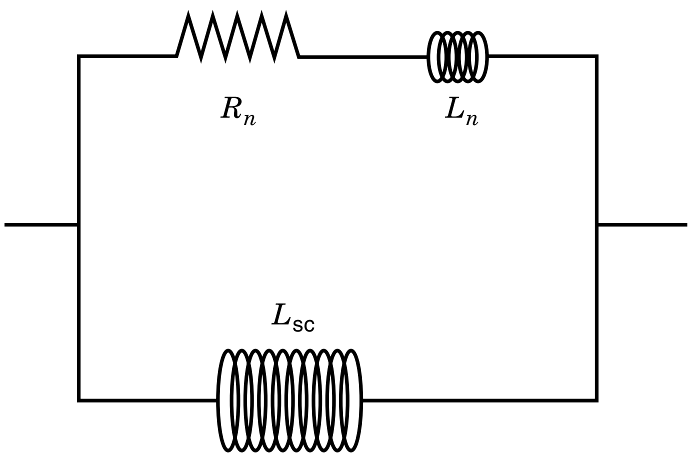

Figure 1. Two-fluid model equivalent circuit of a superconductor.

increase with frequency. A superconductor can be regarded as being composed of two types of charge carriers, one consisting of the lossless Cooper pairs and the other being lossy "quasiparticles." Such a description is known as the "two-fluid model" and is applied to all known superconductors.

The finite frequency [alternating current (ac)] response of a superconductor is characterized in terms of a generalization of Ohm's law: $\boldsymbol{J} = \sigma_s \boldsymbol{E}$, where $\boldsymbol{E}$ is the applied electric field and $\sigma_s = \sigma_1 - i\sigma_2$ is the complex conductivity. The normal part σ_1 comes from the motion of the quasiparticles, and the imaginary part σ_2 comes from that of the Cooper pairs. For most superconductors well below the transition temperature, $\sigma_2 \gg \sigma_1$. The frequency ω, wave vector $\boldsymbol{k}$, temperature T, and current density $\boldsymbol{J}$ dependence of σ_s contains all the information about the electrical properties of the superconductor. For a normal metal, $\sigma_s = \sigma_n$ is purely real.

Figure 1 shows a lumped circuit equivalent of a superconductor. The large inductive element L_{sc} represents the lossless carriers, and the parallel branch with a series combination of a resistor R_n and an inductance L_n represents the quasiparticles. At dc, the large inductor shorts out the resistive branch, leading to zero resistance, while at finite frequencies there is always dissipation.

As the excitation frequency increases, the impressed electromagnetic field is confined closer to the surface. In a normal metal, this is known as the skin effect and the characteristic length of confinement (the "skin depth") is given by $\delta_n = (2/\mu\omega\sigma_n)^{1/2}$ where σ_n is the (normal) conductivity. δ_n for Copper at 10 GHz and 77 K is 0.55 μm. In a superconductor at temperature $T \ll T_c$, the skin depth is replaced by the "London penetration depth" $\lambda_L = 1/(\mu\omega\sigma_2)^{1/2}$. The penetration depth is typically independent of frequency from dc to microwave frequencies and is comparable to the London penetration depth in Table 1.

The interaction of a time-varying electromagnetic field and a metal (normal or superconducting) at microwave frequencies is best described in terms of the surface impedance defined as $Z_S = R_S + iX_S = (i\mu\omega/2\sigma)^{1/2}$. R_S and X_S are the surface resistance and reactance, respectively. As can be seen from the above discussion, R_S and $X_S \propto \omega^{1/2}$ in a normal metal, where $\sigma = \sigma_n$. On the other hand, $R_S \propto \omega^2$ and $X_S \propto \omega$ in an "ideal" superconductor. This can be easily verified by assuming σ_1 and λ_L to be frequency-independent and $\sigma_2 \gg \sigma_1$.

The property that makes superconductors attractive for passive microwave circuits is that their surface resistance is orders of magnitude lower than that of normal metals. For example, thin-film YBCO has a surface resistance of <0.1 mΩ

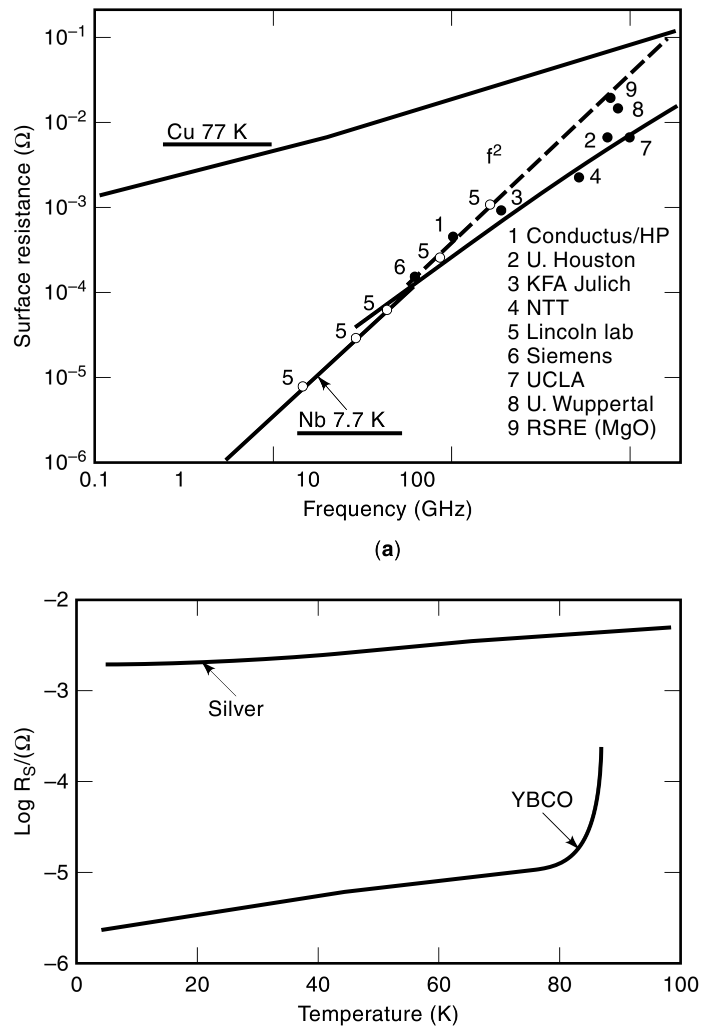

Figure 2. (a) Comparison of the surface resistance of YBCO at 77 K with other superconducting materials. The gray bands represent YBCO. (From Ref. 3, with permission.) (b) Temperature dependence of the surface resistance of YBCO grown by a number of techniques compared with niobium and niobium–tin superconductors at the same reduced temperature. The scale on the upper axis refers to the reduced temperature for the Nb_3Sn and Nb, while the lower scale refers to the actual temperature of the YBCO films. The T_C of the three materials coincides. f = 8 GHz.

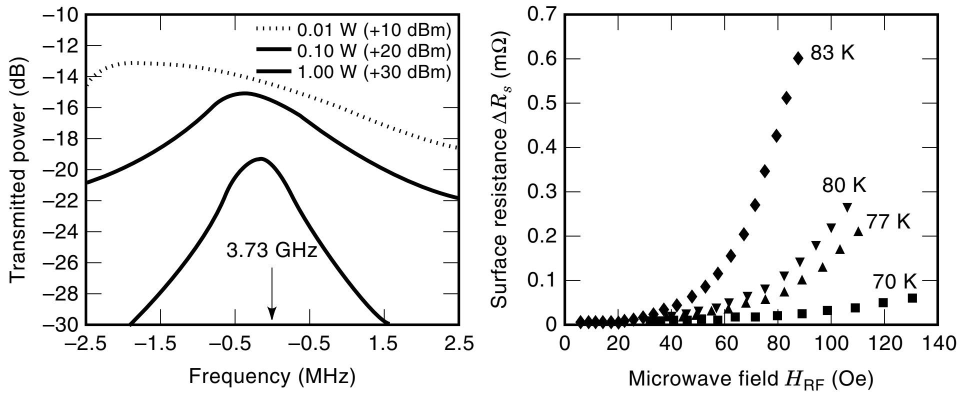

Figure 3. (Left) Frequency-domain response of a suspended resonator. Notice the deviation from a Gaussian shape as the input power increases. (Right) The R_S of a similar resonator against applied power at different temperatures. (From Ref. 4, with permission.)

at 77 K and 10 GHz compared to 8.7 mΩ of copper under identical conditions, and this difference is even higher at lower temperatures. Figure 2 shows the measured frequency and temperature dependence of R_S of some of the most common superconducting and nonsuperconducting materials (3).

Nonlinearity in High-T_C Superconductors

For most superconductors, particularly the high-T_C superconductors, the surface impedance increases with applied microwave power, even for moderate power levels ($<$0.1 W). In other words (unlike normal metals), they act as nonlinear circuit elements. This nonlinear response often poses serious constraints on the utility of superconductors in practical devices. Some specific examples of such limitations are as follows:

- Degradation of insertion loss with increasing power.
- Generation of harmonic frequencies: For an applied signal at frequency f, most of the harmonic power is generated at a frequency of $3f$. Given today's tight use of the electromagnetic spectrum, practically all frequency ranges have been preassigned by the appropriate authorities (e.g., the Federal Communication Commission in the United States) with just the required amount of bandwidths. Thus, radiation by a device at frequencies far outside the designated frequency of operation is unacceptable.
- Frequency mixing, leading to intermodulation products (intermods): For two nearby frequencies f_1 and f_2, the strongest intermods are produced at $2f_1 - f_2$ and $2f_2 - f_1$. The result is that spurious frequencies are produced in devices.

Figure 3 shows the effect of nonlinearity on a suspended line resonator with a resonance frequency of 3.73 GHz (4). At low power levels the response in the frequency domain is close to a Lorentzian. As the input power is increased, the shape begins to distort, and the Q and the resonance frequency go down. This also highlights the point that at high power levels the Q of a superconducting resonator cannot be defined in terms of a "3 dB bandwidth." A quantitative measure of the nonlinearity of a device is specified in terms of its third-order intercept (TOI), defined as the input power at which power output at the fundamental and the third harmonic equal each other. Single-tone TOI for most commercially used HTSC materials is at least 70 dBm (10 kW).

All these effects together limit the maximum power that a passive superconducting circuit can handle, and raising the power handling capacity has been one of the prime concerns of material scientists and engineers alike. Much of the nonlinearity of the high-T_C materials is ascribable to material properties (e.g., granularity and "flux pinning") and is expected to improve with synthesis and deposition techniques. From a design point of view, nonlinearities can be suppressed by increasing the surface area of the device, leading to lower current densities and avoiding current crowding at the edges. Thus, a planar filter can handle significantly higher power than a stripline, and a cavity resonator has Q value orders of magnitude higher than one built out of a transmission line, even factoring out the losses in the substrate. However, higher-dimensional circuits are not always practical for many applications because they take up more space and often have the problem of mode degeneracy (i.e., more than one mode of oscillation at the same frequency). The latter problem can often be solved by making the circuit slightly asymmetrical, but then modeling them with a computer becomes more cumbersome.

PASSIVE MICROWAVE CIRCUITS

Passive microwave circuits are some of the most promising applications of superconductors to date. In the following we shall focus on the advantages of high-temperature superconductors (HTS) materials and the special considerations that applies to them. General ideas about passive microwave devices are available in the literature. For a good review of the current state of the art, see Ref. 5. For a more elementary introduction, see Ref. 6.

Superconductors are an attractive alternative to "conventional" materials for three principal reasons:

1. *Very low surface resistance* compared to normal metals: For example, insertion loss of a superconducting filter ($\sim$0.1 dB) is usually at least 3 dB lower than one made out of high-quality metal (e.g., oxygen-free high-purity copper) under equivalent conditions. Thus in applications where the signal strength is low, superconductors are the material of choice.

2. *A frequency-independent penetration depth.* In normal metals, the skin depth is proportional to the inverse square root of the frequency of the signal, giving rise to strong dispersion of a wide-band signal, unacceptable in many applications. In superconductors, the penetration of electromagnetic field is dominated by the "London penetration depth," which is independent of frequency, giving rise to phase-dispersion free propagation in the TEM mode.
3. *The ability to be fabricated in extremely compact geometries,* arising from the low loss mentioned above. Thus, a several-meter-long coaxial delay line made out of a normal conductor can be replaced with a superconducting one that's only a few square centimeters in area, and bulky dielectric resonator filters can be replaced by compact planar superconducting filters.

Transmission Line

A microwave transmission line can be constructed in several geometries, each having its pros and cons. The most common geometries are microstrip, stripline, and coplanar. Many other novel geometries such as the suspended line and coplanar strips are also used for special-purpose applications. The basic concepts behind transmission line and distributed circuits is the same whether or not they are made out of superconductors, and the interested reader can find them elsewhere (see, for example, Ref. 7). Here we will briefly discuss only those issues that are specific to superconducting transmission lines.

The two major distinctions between superconducting and nonsuperconducting transmission lines stem from the temperature and frequency dependence of the characteristic impedance of the line, defined as $Z_0 = (L/C)^{1/2}$ where L and C are the equivalent lumped inductance and capacitance, respectively. In addition to the usual geometric inductance, superconductors have temperature-dependent kinetic inductance because of the presence of the Cooper pairs. Also, for sufficiently low temperatures ($T \ll T_C$, or more pertinently, $\lambda_L \ll \delta$) the penetration depth is independent of the frequency, giving rise to a phase dispersion free propagation for the TEM mode. Nonlinear effects are another major complication in dealing with superconducting transmission lines as has been discussed earlier. The nonlinear effects are particularly worse in the edges of the line where the current density is maximum. Therefore, a good design for a passive superconducting circuit tends to avoid sharp edges as much as possible. Owing to these, full-wave analysis of superconducting transmission lines is quite a daunting task which cannot be done satisfactorily using most commercially available CAD programs and often must be carried out for individual needs.

One of the most promising applications of superconducting transmission lines is in the form of hybrid interconnects between components, both semiconducting and superconducting and both analog and digital.

Resonators

The "quality factor" (Q) of a resonator is defined to be $Q = Uf_0/P$, where U is the total energy stored in the oscillator, f_0 is the resonance frequency, and P is the power dissipated per cycle. Since $P = \int R_S H^2 \, dA$, where the integral is over the surface of the material comprising the resonator walls, the Q can then be written as $Q = \Gamma/R_S$, where Γ is a geometric factor, for a resonator comprised entirely of a single material.

The advantage of a superconducting resonator over a normal metal one is the very high Q owing to the much smaller surface resistance of the former. At 10 GHz, Q as high as 10^{11} can be achieved (using niobium cavities in TE_{011} mode), compared with a maximum Q of around 10^4 using copper. Superconducting cavities are typically operated in the TE_{011} mode since this has no electric fields on the cavity walls. Cavities have been made out of both low-temperature and high-temperature superconductors (8), although the latter is a lot harder to make owing to the ceramic nature of the material. Superconducting cavities such as these play an important role as a research tool for precision measurements of surface impedance of superconductors and other materials. Figure 4 shows a picture of a niobium cavity that was fabricated at Northeastern University and is used to measure the surface impedance of other crystalline superconductors using the cavity perturbation technique (9).

A major application of superconducting cavities is in providing large high-frequency electric fields for accelerating subatomic and atomic particles. The fields in a cavity resonator are given by $E_{max} = \gamma(QP_{abs})^{1/2}$, so that significantly larger fields can be achieved with high-Q cavities for much lower absorbed powers P_{abs}. A notable example is the continuous electron beam accelerator facility (CEBAF) for heavy ions, which uses superconducting niobium cavities operating at megahertz frequencies.

Superconducting microwave cavity resonators are among the most stable frequency standards available today owing to their very high Q values. One of the applications of such high stability frequency standards is in satellite and deep space communications, where it is important to maintain precise clocks on board the satellite to improve synchronization between the ground-based clock and the satellite or space vehicle's on-board clock.

Another potential application is in the master oscillator of a Doppler radar. A Doppler radar identifies the target velocity by measuring the frequency shift of the reflected beam. Clearly, for the measurement to be reliable, the frequency of the source has to be highly stable. This is especially important for detecting targets flying close to the ground (e.g., a cruise missile), since reflections from the ground (the "ground noise") can completely mask the signal.

Filters

A filter is realized by a set of coupled resonators with closely spaced resonance frequencies. The response of each resonator is represented as a pole in the frequency domain. Thus a filter with n resonating elements is called an n-pole filter. The resonators can be lumped (e.g., tank LC oscillators) or distributed (e.g., half-wave transmission lines.) Clearly, the greater the number of poles in a filter, the greater the bandwidth that can be achieved for a preset filter skirt and band ripple, or the steeper the filter skirt and smaller the band ripple for a given bandwidth. Both are desirable. However, increasing the number of elements increases the insertion loss proportionally. Thus, many applications which require *both* a small insertion loss and steep filter skirt with low band ripple cannot be realized using conventional materials such as high-purity copper.

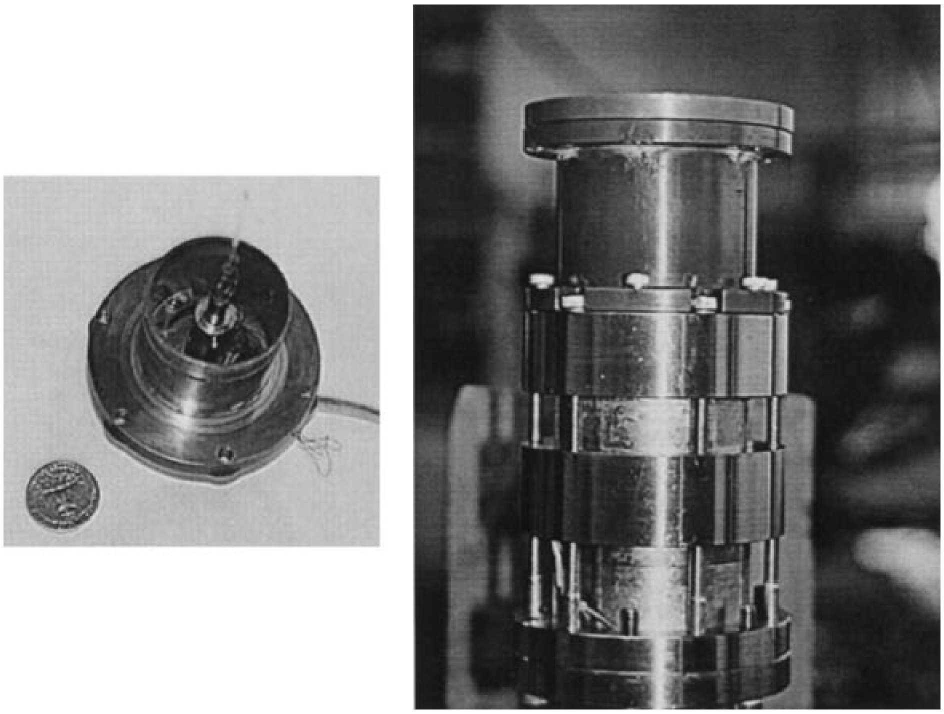

Figure 4. A superconducting niobium cavity used for surface resistance measurement. The specimen under test is thermally insulated from the cavity using a sapphire rod, allowing it to be probed up to nearly room temperature while the cavity is still superconducting. (Right) The disassembled cavity showing the sapphire sample mount. (Left) The packaged structure. Q values of $\sim 10^7$ to 10^8 at 4.2 K are routinely obtained in this setup. (Courtesy of Z. Zhai and H. Srikanth.)

Alternative technologies such as surface acoustic wave (SAW) devices do produce better results, but are still too lossy (typically 2 dB to 4 dB). Dielectric resonator based filters have low loss, but are too bulky for many lucrative applications. This is precisely why superconductors are the material of choice for making high-performance filters. The extremely low surface resistance allows a designer to use a lot more ments for a given amount of insertion loss.

Figure 5 shows a four-pole microstrip Chebyshev filter ricated at the MIT Lincoln Laboratory with a 4.8 GHz center frequency and 100 MHz bandwidth patterned on an $LaAlO_3$ substrate with YBCO film. The filter uses a "hair pin try"; that is, the resonators are bent with a U-turn to save wafer space. The right-hand side of Fig. 4 shows the sured insertion loss (S_{21}) of the filter at 77 K temperature. Also shown for reference is the performance of equivalent ters made out of silver (Ag) at 77 K and gold (Au) at room temperature (300 K). The advantages of high-T_C superconducting filters are quite obvious.

One of the problems in working with HTS material is the lack of availability of large wafers of acceptable quality. The maximum size of high-quality HTS films are presently limited to about 5 cm, compared to 30 cm wafers of semiconductors. This poses a problem in two cases: (1) where the center frequency is low, requiring the length of the transmission lines of a distributed filter to be long, and (2) where the bandwidth is tight (a fraction of 1%), requiring very weak coupling, and hence large separation between elements. The first problem calls for miniaturization of the device, and there are several means of accomplishing this, including the use of lumped resonators (10) and high-dielectric-constant substrates. The second problem is usually solved by a technique called staggering. Figure 6 shows a photograph of a high-performance lumped-element nine-pole Chebychev filter.

Frequency Agile Devices. A filter is much more useful if it can be tuned. Several innovative approaches to tune a passive filter have been tried. One method consists of changing the

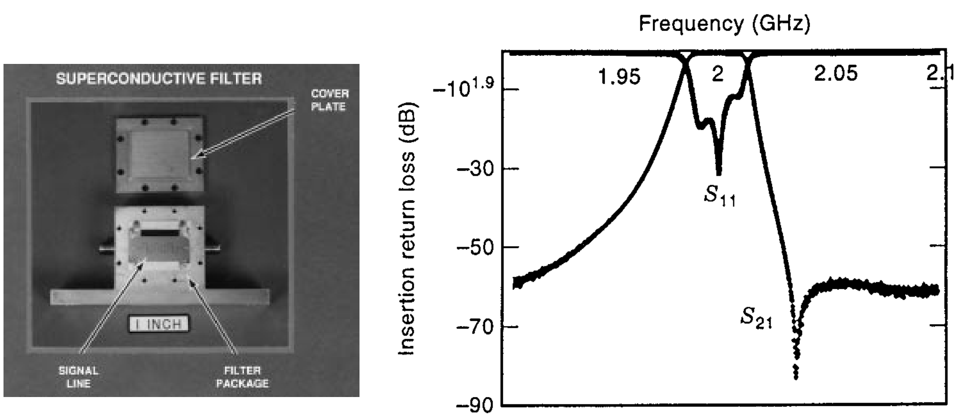

Figure 5. A four-pole superconducting filter and its measured performance. (Courtesy of Dr. Daniel Oates, MIT Lincoln Laboratory.)

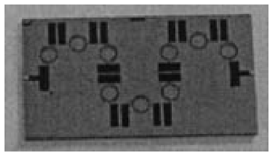

Figure 6. A nine-pole lumped Chebychev filter from Superconductor Technologies Inc. (Courtesy of Dr. Balam Willemsen, Superconductor Technologies, Inc.)

resonance frequency of the individual resonators (due to change in the kinetic inductance) with temperature. The desired variation in temperature is achieved by a control line in the form of a heating element placed close to the resonators. A better method is to build the filter on a ferroelectric substrate with a low Curie temperature such as $KTa_{1-x}Nb_xO_3$ and $Sr_{1-x}Pb_xTiO_3$ (11). The permittivity of the substrate can be changed by applying a bias voltage, thus providing the necessary tuning. The optimal temperature of operation is slightly above the Curie temperature of the substrate to avoid hysteresis and to produce maximum tunability for a given bias voltage. Impedance matching of the input and output is done with a set of ferroelectric transformers. Since these techniques essentially manipulate the electrical length of the filter elements, the same methods can also be used to tune the parameters of other passive structures.

Another important type of filter is a "chirp" filter. A "chirp" is essentially a frequency-modulated signal whose frequency increases ("up-chirped") or decreases ("down-chirped") with time. One of the applications of chirp signals is in Doppler radars to optimize power output and bandwidth, both of which are desirable. Using a simple sinusoidal signal, however, both cannot be achieved simultaneously. A higher bandwidth means a shorter pulse width which limits the maximum power transmitted per pulse and vice versa. A chirped waveform gets around this limitation. Another application is to compensate the distortion of a wave packet after passing through a dispersive transmission line. The principal advantage of constructing a chirp filter out of superconducting material is low dispersiveness.

A superconducting chirp filter in microstrip geometry consists of a series of quarter-wave forward-coupled transmission lines which are deliberately decoupled for a specified length between the couplings. The transmission line is wound in the form of a spiral to optimally use the film surface. As a pulse is applied to the input, the individual frequency components couple to the output line that corresponds to their resonance frequencies. Depending on whether the resonators are increasing or decreasing in length down the line, a down-chirped or up-chirped signal is obtained at the output.

Antenna

Using superconducting antennas can improve efficiency enormously because of their lower loss (for a general discussion of antennas, see Ref. 12). In particular, there are three situations when a superconducting antenna can outperform one made out of a normal metal sufficiently to merit its use:

1. *Electrically Short Antennas.* A dipole antenna has maximum radiation efficiency when its characteristic length is an integral multiple of the wavelength being radiated. For low-frequency applications (such as underwater communication, which involves frequencies of the order of 15 kHz), this length can be unrealistically large, and hence a shorter antenna has to be deployed. The radiated power P is proportional to $(l/\lambda)^2$ for a linear (electric dipole) antenna and $P \propto (D/\lambda)^4$ for a circular loop (magnetic dipole) antenna, where l is the length of the linear antenna, D is the diameter of the loop antenna, and λ is the radiated wavelength. For l, $D \ll \lambda$, the impedance of the antenna is mostly reactive and most of the power is dissipated as ohmic losses in the antenna and the feed network. Therefore, introduction of superconducting radiating elements and feed networks can dramatically improve the radiation efficiency at low-frequency regions.
2. *Superdirective Antennas.* A superdirective antenna (13) has directional gain much larger than a conventional one. This can be of advantage in radio beacons and radar transmitters. A superdirective antenna is realized in practice by an array of closely spaced (separation $\ll$ wavelength) dipole elements that are excited approximately 180° out of phase with respect to their neighbor. Such a structure has a low efficiency when built out of normal metal because ohmic losses in each individual element add up. In addition, these antennas have inherently low radiation efficiency because of cancellation of the radiation field, and use of HTS material can enhance efficiency.
3. *Millimeter-Wave Antennas and Feed Networks.* Superconducting antennas also improve the performance of antenna arrays and other distributed feed systems, where the power gain because of the distributed structure has to compete with the loss in an increasing number of elements. In a copper microstrip antenna the overall gain begins to decrease beyond about 40 elements, whereas the same antenna employing superconducting elements shows an increase in gain up to about 400 elements. This increase in gain can be crucial in mission critical applications such as military target tracking systems.

Figure 7 is a photograph of a 16-element phased-array antenna that was developed at the US Air Force Rome Laboratory.

Delay Lines

Requirements for a good delay line are low loss, low dispersion, and large delay for unit size/weight of the material. Superconducting delay lines are far superior to normal metal ones in satisfying these requirements, so much so that superconducting delay lines were in application even before the advent of high-T_C superconductivity (14). Delays of the order of 20 ns can be routinely achieved with HTS materials on a substrate with an area of a few square inches, with good possibilities of achieving more than 100 ns in the near future. A copper coaxial line has to be several meters long for producing the same amount of time delay and would also have a high insertion loss.

A novel application of a delay line is the measurement of instantaneous frequency of a nonperiodic signal (15). This is achieved by splitting the input signal power equally between a series of n phase discriminating units, where n is the number of bit of frequency resolution desired. Each phase discrim-

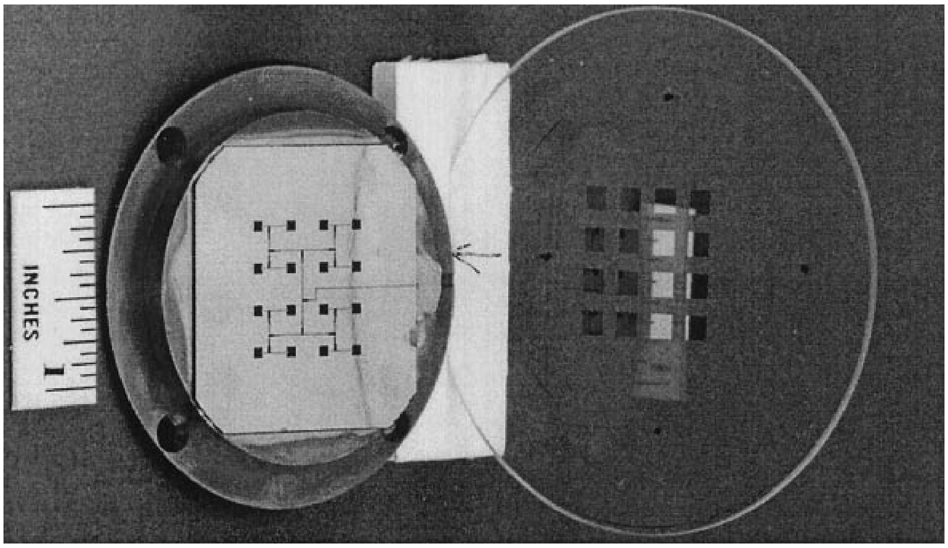

Figure 7. A 16-element superconducting phase array antenna and the feed network. An $LaAlO_3$ substrate is holding the HTS film. To the right of it is a 1 mm quartz plate holding the corresponding copper patches that provides an electromagnetic coupling to room temperature environment. A 0.5 mm vacuum between the two and low thermal conductivity spacers provide the required thermal isolation. The quartz plate has the necessary mechanical strength to withstand the atmospheric pressure and also serves as a radome. The antenna operates at 20 GHz. (Courtesy of Dr. Jeffrey Herd, US Air Force Research Laboratory.)

inating unit consists of a mixer, one port of which is fed by the signal directly and the other one by the same signal delayed.

ACTIVE MICROWAVE CIRCUITS

In 1962 B. D. Josephson predicted that when two superconductors are separated by a thin layer of metal or an insulator, a lossless current can flow upto a certain critical value I_C before a voltage appears across the junction. This is the manifestation of the phenomena that the Cooper pairs that carry lossless electric current can tunnel through the potential barrier represented by the junction material. Josephson's remarkable prediction was verified experimentally the following year and is known as the Josephson effect. The Josephson effect opened the way for a number of new applications of superconductors which exploit the fact that superconductivity is actually an amazing manifestation of quantum mechanics on a macroscopic scale. The most noteworthy of these is the superconducting quantum interference device (SQUID) magnetometer. With sensitivities approaching 10^{-15} T/Hz$^{1/2}$ values, SQUIDs can measure magnetic field with precision that is unimaginable with any conventional techniques. The interested reader is referred to some useful reference for further details (see, for example, Ref. 16). In the following, we shall describe some of the microwave applications of the Josephson effect that have the potential to radically alter the future of microelectronics.

The Josephson current I is related to the phase difference θ between the Cooper pair on the two sides of the junction as $I = I_C \sin\theta$. When current across the junction exceeds the critical value, a voltage V appears across it that is related to time rate of change of θ as $\partial\theta/\partial t = 4\pi eV/h$ (i.e., the phases of Cooper pairs on the two sides of the junction begin to "slip" relative to each other.) Figure 8(a) shows a lumped circuit equivalent of a Josephson junction (JJ), called a resistively shunted junction (RSJ model). The conductance and the capacitance represent the resistive and displacement current flow across the junction. The static characteristics of the circuit is given in terms of Stewart–McCumber parameter (17,18) $\beta = 4\pi eI_CC/hg^2$.

Elementary mathematical analysis of Fig. 8(b) shows that the time-domain response of the circuit can be written as $I/I_C = \beta d^2\theta/d\phi^2 + d\theta/d\phi + \sin\theta$, where $\phi = 4\pi eI_Ct/hg$, t being time. This is equivalent to the equation describing the motion of a simple pendulum in a gravitational field. Thus the Josephson current behaves like a damped harmonic oscillator for small currents which is underdamped for $\beta < 1/4$ and overdamped for $\beta > 1/4$. This also implies a hysteretic I–V behavior in the a region $I_{min} < I < I_C$, and the value of I_{min} must be obtained by solving the above equation. The value of I_{min} decreases monotonically with increasing β. Another useful property of a JJ is the flux dependence of the critical current. If the JJ has a flux Φ threaded to it, then the critical current is given by $I_{C\Phi} = I_C \sin(\pi\Phi/\Phi_0)/(\pi\Phi/\Phi_0)$, where $\Phi_0 = h/2e = 2 \times 10^{-15}$ Wb is the "flux quantum." (The flux threaded through any superconducting ring must be an integral multiple of Φ_0.) This is shown in Fig. 8(c).

To date, the most promising applications of superconducting active devices have been demonstrated only in low-temperature superconductors, most notably lead, niobium, and niobium nitride with aluminum oxide (AlO_x), magnesium oxide (MgO), and lead oxide (PbO) as the insulating barriers. For a Cooper pair to tunnel coherently across a junction, its thickness must be comparable to the coherence length of the material, which is extremely small for high-T_C superconductors (see Table 1). The critical current in these materials is also rather high (of the order of milliamperes), which is required for the Josephson coupling energy $hI_C/4\pi e$ to overcome the thermal energy k_BT, but it produces excessive Joule heating in the resistive shunts and high voltages across inductances. There are additional factors arising out of complex crystal structure and presence of "weak links" (i.e., small-angle grain boundaries) that make fabrication of JJs difficult in these materials. There are several possible analog and digital applications of the Josephson effect in microwave frequency regime, some of which are outlined in the following.

Superconducting Digital Logic Circuits

From the early days of its discovery, the Josephson junction (JJ) has been eyed as a potential replacement of semiconducting logic gates (a detailed review is provided by Ref. 19). Josephson junctions are inherently bistable (with zero and finite resistivity). However, the real driving force behind a "super-

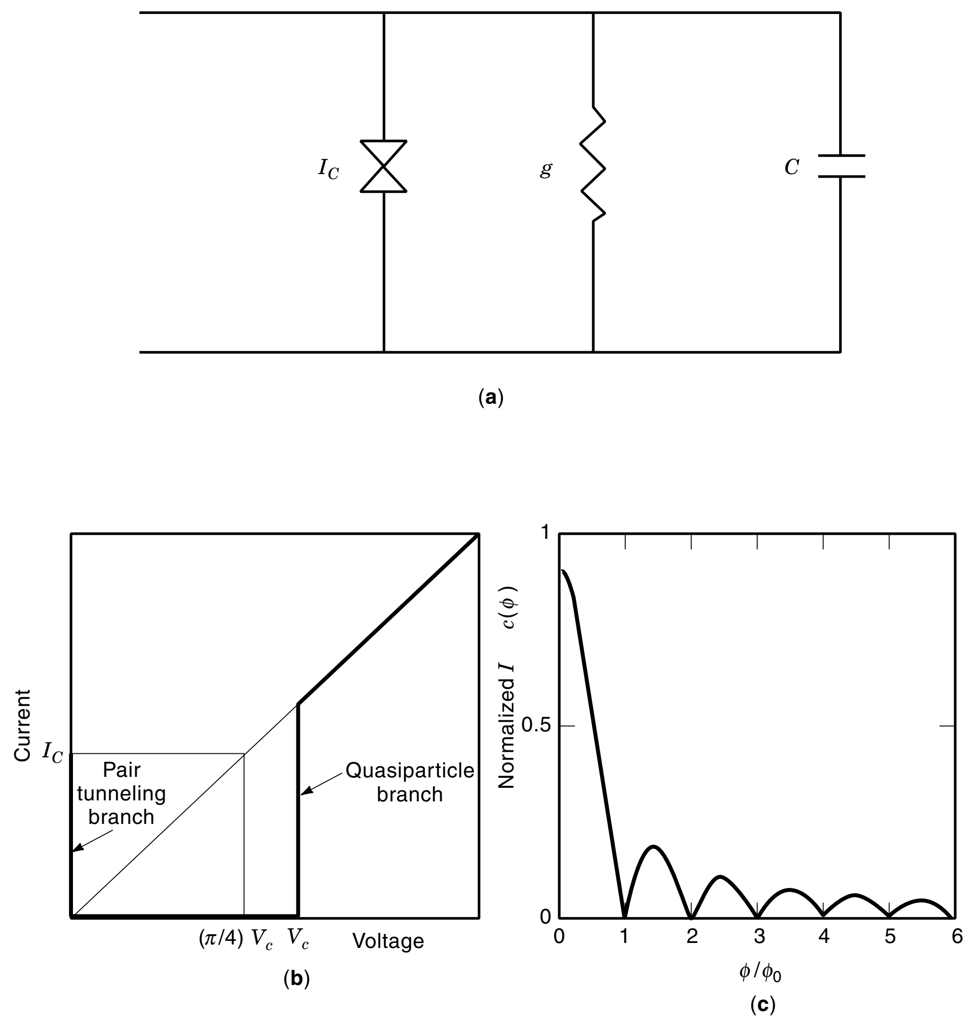

Figure 8. (a) Lumped equivalent of a superconductor–insulator–superconductor (SIS) Josephson junction. (b) I–V characteristics of an SIS Josephson junction. (c) Dependence of junction critical current on the threaded flux.

conducting supercomputer" comes from three different sources:

- Josephson junctions can be switched *much* faster than a CMOS logic gate, where the parasitic and junction capacitance limits the minimum switching time. For a JJ, however, the theoretical limit on switching time is $h/2\pi\Delta$, where h is Planck's constant and Δ is the superconducting energy gap. For niobium, this corresponds to 0.22 ps, and practical circuits with switching times of 1.5 ps have been fabricated. The large difference between the theoretical upper limit in switching speed and those practically achieved stems from parasitic capacitance in the junction. However, there are no space-charge effects in a JJ, and hence these capacitances are much smaller compared to semiconductor circuits.
- Average power dissipation per gate in a JJ is at least two orders of magnitude lower than equivalent semiconductor gates. This means that the gates can be packed closer together, thereby reducing the propagation delay of the signal, another constraint in high-speed digital circuits. As an example, a four-bit microcontroller fabricated out of JJ and clocked at 770 MHz dissipated 5 mW, in contrast to a replica made out of gallium arsenide (GaAs) and clocked at 72 MHz that dissipated 2.2 W.
- Digital circuits operating over ~100 GHz must use superconducting interconnects, because the inherent dispersion and loss in metal interconnects will degrade the signal sufficiently to make the circuit inoperable.

Owing to the hysteretic I–V characteristics of the JJ, switching between zero resistance and finite resistance states (logic 0 and logic 1 in our convention) cannot be achieved as fast as it would be in a nonhysteretic device. If the current is reduced slightly below the value at which a logic 0 to logic 1 switching takes place, the circuit will remain in logic 1 state. Owing to this property, such circuits are called "latching circuits." The maximum clocking speed of these circuits cannot exceed a few gigahertz. To solve this problem, JJs are shunted with resistors that make them nonhysteretic. These circuits, called rapid single flux quantum (RSFQ) devices, are the basic building block of superconducting logic circuits. They differ from "conventional" logic in a fundamental way: The logic state is not decided by the voltage level of the gate but by the presence or absence of voltage pulse generated by the motion of single fluxons. Practical superconducting digital circuits with significantly higher performance have been demonstrated. Using niobium technology, a 4 bit microprocessor has been fabricated by Fujitsu and a 1 kbit random access memory (RAM) chip has been made by NEC (for a good review of recent progress in Josephson IC fabrication, see Ref. 20). Many other leading manufacturers are also pursuing this technology (21).

There are a few rather unusual problems in the practical realization of a superconducting computing device. It is impractical to realize a high-speed computer in a Von Neumann-type architecture that involves massive data transfer between a central processor and the memory, which are physically separated over a relatively long distance. An order-of-magnitude estimate of the maximum allowable data path (assuming microstrip interconnects on a substrate with dielectric constant ~20) of a computer operating at 300 GHz is ~0.3 mm. Clearly, this is very difficult to realize on a circuit board. However, applications such as dedicated digital signal processor with on-board cache memory and multichip modules can have phenomenal speed and performance increase if built using RSFQ logic.

Detectors and Mixers

The nonlinearity of a Josephson junction can be exploited to make a mixing device. In addition to the low noise and high efficiency that these devices offer, they can easily be integrated to an all-superconductor radio-frequency (RF) receiver front end.

The general principles of mixing due to photon-assisted tunneling was derived and applied to superconductor–insulator–superconductor (SIS) junctions by Tucker (22,23). There can be two types of mixers using Josephson junctions: those using Cooper pair tunneling operating near zero bias voltage and those using quasiparticle tunneling operating near gap voltage. Quasiparticle mixers are usually preferable over Cooper pair mixers for several reasons. For one, the junction capacitance has to be small so that most of the current comes from Cooper pair tunneling and not displacement electric field. This means the use of point contact junctions which are difficult to fabricate reproducibly. Secondly, they are noisy because of harmonic mixing of all frequencies up to the gap frequency. According to the quantum theory of mixing, strong nonlinearity in I–V characteristics (more precisely, when $I_{dc}(V_{dc} + h\nu/e) - I(V_{dc}) \gg I_{dc}(V_{dc}) - I_{dc}(V_{dc} - h\nu/e)$ can result in conversion gain exceeding unity and conversion efficiency approaching the quantum limit even in a purely resistive mixer. Thirdly, the shot noise in a quasiparticle mixer is lower than that in Cooper pair tunneling mixers. SIS quasiparticle mixers have been used in radio astronomy for quite a while.

Analog-to-Digial Converters

Analog-to-digital converters (ADCs) are another type of circuit where phenomenal performance improvement has been demonstrated using superconducting circuitry. While superconducting ADCs can be and have been fabricated in most architectures and have the usual advantage of a large bandwidth because of their fast switching capability, there is the additional advantage that when exploiting the multithreshold characteristics of a JJ [see Fig. 8(c)], an n-bit flash ADC requires only n comparators as opposed to $2^n - 1$ that would be normally required (24). This allows high-bandwidth and high-resolution ADCs to be fabricated reliably and compactly.

Precision Voltage and Frequency Sources

The Josephson relation $\partial\theta/\partial t = 4\pi eV/h$ can be used both as a source of high-frequency radiation and a dc voltage standard. The power radiated by the oscillating Josephson current in response to a small dc bias (483.5 GHz/mV) is usually too very small (a few nanowatts) to be of much practical use, but coherent Josephson arrays have been fabricated that can output as much as a few microwatts, and power levels of up to 1 W has been predicted. On the other hand, when irradiated with microwaves, a JJ develops a dc voltage across it. Since frequency of such radiation can be accurately controlled and measured, such devices are one of the accepted precision voltage standards today.

The Future of Superconducting Microwave Electronics. How are these myriad of possible superconducting circuits realized in practice? Just like any other microelectronic circuit, they are lithographically patterned on a substrate through a similar sequence of steps an in a semiconductor (25). Thus, the vast assortment of techniques developed during the last several decades for and by the semiconductor industry can be ported into commercialization of superconducting electronics. For a complete self-contained system, many of the subsystems have to be built out of semiconductor devices [e.g., the (IF) amplifiers for an RF transceiver]. An efficient way of manufacturing these systems is to mix HTS and high electron mobility transistor (HEMT) semiconductor circuits on the same substrate as a multichip module (MCM) (26). Typically the HTS film is grown on a GaAs substrate with a thin buffer layer for better lattice match. Semiconductor devices perform better at lower temperatures because of enhanced carrier mobility, so the overall performance increases. Decrease of thermal noise is another desirable byproduct. Also, with the increase in the packing density of the semiconductor circuitry, a decrease in operating temperature, and the advent of high-temperature superconductors, the disparity between the operating voltage levels associated with the two types of circuits is going down, minimizing the possibility of ground loops between these two types of elements. Any large-scale commercial application of HTS microwave circuit will rely on the ability to integrate them, either as a hybrid component or as a monolithic component, with active semiconductor components.

There are many hurdles in the road to success of superconducting devices. The absence of a room-temperature superconductor, essential for consumer market, is one of them. Even if there were a room-temperature superconductor, the vast amount of techniques developed by the semiconductor industry for precise and predictable control of material properties are unavailable in the superconductor industry. The reason for this is obvious: The whole phenomenon of high-temperature superconductivity is only understood phenomenologically at best. There is no equivalent of "bandgap engineering" for superconductors. If we knew the material to dope to change the superconducting bandgap, we could then produce a room-temperature superconductor!

However, consumer electronics, though a large share of the market, still is not all of the market. There are niche markets, mostly in the defense sector and commercial/military wireless communication, who would pay the extra dollar to have the advantages of superconducting electronics (see, for example, Ref. 27). For example, the low insertion loss and steep skirt of a superconducting filter makes it cost effective in a cellular base station where the receiving/transmitting antenna must operate within tight bandwidth tolerance and divide up the available bandwidths among as many customers as possible. Such filters are available from many vendors and several are being field-tested by cellular service providers. One example of a large-scale attempt to use HTSC microwave circuits in communication application is the United States Naval Research Laboratory's "High Temperature Superconductivity Space Experiments" (HTSSE) (28). The US Air Force is another major player in this field and expects to utilize low-loss superconducting antennas in the next-generation radar systems. System integration is a crucial aspect toward commercialization, and significant progress has been made to this end. Integration of individual superconducting microwave components to produce a complete self-contained RF receiver/transmitter front end has been successfully demonstrated by many researchers. Integration of superconducting and semiconducting electronics on the same device has also been carried out.

At the present rate of progress, we can safely say that the growth of superconducting electronics will steadily increase with time. Whether it would radically alter the present state of the art, similar to the effect the advent of solid-state circuits had over the vacuum tube technology, will be seen in the years to come.

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SUGGESTIONS FOR FURTHER READING

The literature of microwave applications of superconductivity is quite extensive, and citations relevant to a particular subtopic have already been given wherever appropriate. A nonexhaustive list of periodicals and monographs of general interest in this area is provided below:

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