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High-Temperature Cuprate Superconductors Get to Work

Discovered two decades ago, these complex materials are poised to enter the commercial marketplace in a number of unanticipated applications.

Alexis P. Malozemoff, Jochen Mannhart, and Douglas Scalapino

The cover story in the 11 May 1987 issue of *Time* magazine featured the discovery of high-temperature superconductors (HTSs) announced the previous year by the 1987 Nobel laureates Georg Bednorz and Alex Müller.[1] The 1987 article described HTSs as a "startling breakthrough that could change our world," and made euphoric predictions of a handful of superconducting cables funneling electricity to an entire metropolis, of powerful lightweight HTS motors, and of superconducting quantum interference devices (SQUIDs) that could detect minute magnetic fields and contribute to medical research and other fields. It also noted an alternate view, expressed by theorist Robert Schrieffer, cowinner of the 1972 Nobel Prize with John Bardeen and Leon Cooper for the development of the Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity. Schrieffer argued that the most important applications were probably not yet conceived. Such had been the case, he said, for the transistors used in large-scale integrated circuits. In the 1980s, low-temperature superconductors, too, enabled and found their dominant commercial application in a hitherto nonexistent field: medical magnetic resonance imaging.

Now, nearly two decades after the *Time* report, it is interesting to see which HTS applications are in fact entering our world. (See PHYSICS TODAY, March 1995, page 20.) They do indeed include cables, motors, and SQUIDs. But the HTS applications leading the charge to commercialization were not even mentioned in the early *Time* article and even today are not widely recognized: They are dynamic synchronous condensers for electric power-grid stabilization, microwave filters for wireless-communication base stations, and specialized research magnet systems.

The fundamental novelty of HTS materials was, of course, their high superconducting transition temperature T_c. Those temperatures reached up to 135 K, some six times as high as that of any known low-temperature superconductor.[1,2] The higher transition temperatures imply a corresponding reduction in refrigeration demands that gives HTS materials a major applications advantage. Many obstacles, however, slowed the way toward practical HTS applications, and it is instructive to understand how those barriers have been overcome.

One hurdle was to learn how to make useful materials from HTSs, which are brittle ceramics that exist in multiple phases and morphologies. A second difficulty, in some ways more subtle, was and is to recognize the real advantages that HTSs bring to an application, and to engineer those advantages into cost-effective products.

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The materials challenge

High-temperature cuprate superconductors are among the most complex materials ever explored for practical application.[3] The need to control the chemical composition of these multicomponent compounds at the elevated temperatures (700–800 °C) where high-temperature superconducting structures form, the brittleness of the materials, the volatility of some of their constituents, and the need for nonreactive, lattice-matched, and thermally matched substrates pose serious challenges.

Figure 1a shows the crystal structure of one of the most widely used cuprate superconductors, YBCO ($YBa_2Cu_3O_7$), which has a T_c as high as 93 K. Copper–oxygen planes, through which the dominant supercurrent flows, are a common feature in this and all of the cuprate superconductors. The cuprates' superconducting coherence lengths are short, some four or five times the Cu–Cu spacing in the supercurrent planes. The short coherence lengths imply that local stoichiometry strongly influences such local properties as the superconducting energy gap that indicates the strength of superconductivity. Furthermore, because the energy gap in the cuprates has d-wave symmetry, one needs a high degree of crystalline orientation in the copper–oxygen planes. Grain boundaries separating different crystal orientations act as weak links and become significant obstacles to current flow: Current density decreases exponentially with increasing grain boundary misorientation angle. (See reference 4 and the article by one of us [Mannhart] and Praveen Chaudhari, PHYSICS TODAY, November 2001, page 48.) Avoiding boundaries between misaligned crystallites is another major challenge that must be met to achieve high current flow.

Perhaps the most stringent material requirements apply to thin films, such as filters for cell-phone base stations, that are used in microwave applications. Weak links would lead to microwave losses and unacceptable nonlinear behavior, so very high-quality, grain-boundary-free films are necessary. A general procedure for fabricating such films is to grow them epitaxially on single-crystal substrates. Figure 1b shows such a film. The fabrication

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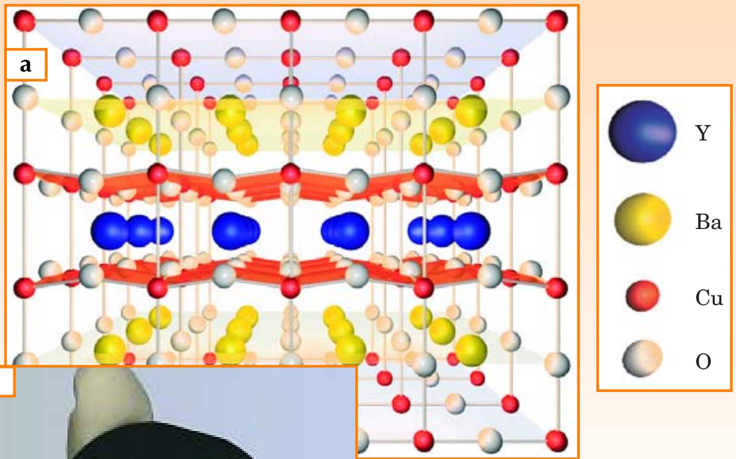

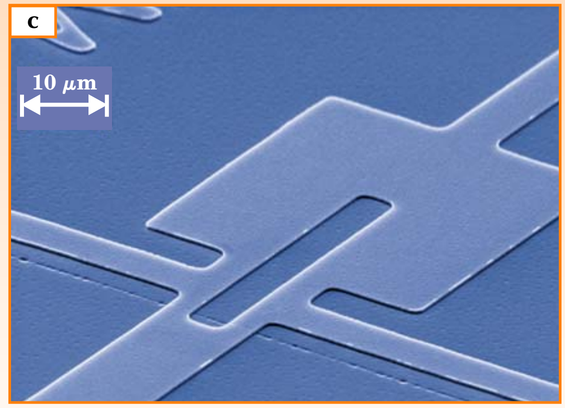

Figure 1. The cuprate superconductor YBCO ($YBa_2Cu_3O_7$). **(a)** In the YBCO crystal structure, yttrium atoms separate two copper–oxygen (CuO_2) planes, and barium atoms separate CuO_2 planes from a layer of CuO chains. **(b)** High-quality, epitaxially grown YBCO films are a component of microwave filters. (Courtesy of Superconducting Technologies Inc.) **(c)** A YBCO film patterned to form a superconducting quantum interference device sits atop a strontium titanate ($SrTiO_3$) bicrystal. In the lower half of this scanning electron microscope image, one can see the 24° grain boundary generating the SQUID's two Josephson junctions. (Courtesy of the University of Augsburg.)

process requires a high substrate temperature (700–800 °C) and ambient-pressure oxygen. But in order that the constituents may be evaporated for deposition, it also requires a reasonable vacuum.

One method that meets those two conflicting demands is the reactive coevaporation technique pioneered at the Technical University of Munich.[5] The Munich group houses their substrates on a rotating platter largely covered by a heated oxygen-rich chamber. As the platter rotates, the substrates briefly exit the chamber and are exposed to yttrium, barium, and copper evaporation sources. Then, as the rotation continues, the substrates reenter the heated oxygen-rich chamber. The resulting films can have a surface resistance at 1 GHz and 77 K of about 2 $\mu\Omega$. That's some 10^4 times lower than the comparable resistance for Cu.

Up to this point, we have focused on difficulties associated with weak links. Some electronic applications, though, exploit such links, which exhibit unique quantum phenomena first theorized by 1973 Nobel laureate Brian Josephson.[6] By growing an epitaxial film over a bicrystal substrate with a grain boundary running across it, one can fabricate weak links, called Josephson junctions, in a controlled manner. Figure 1c shows such junctions in a patterned YBCO film grown over a substrate with a visible grain boundary.

Most high-power applications require flexible, robust, high-current wires that are kilometers in length. The first-generation commercial HTS wire (see figure 2) is a composite of silver or silver alloy and multiple fine filaments of the HTS material BSCCO-2223 ($Bi_{1.8}Pb_{0.3}Sr_2Ca_2Cu_3O_{10}$, with a T_c of 110 K). The wire is made with a mechanical deformation process that aligns the crystalline BSCCO grains within the silver matrix and thus minimizes the grain-boundary obstacles to current flow. Today, one can find commercially available wire, adequate for most power applications, that is 1 km in length and carries current densities greater than 150 A/mm² at 77 K.

A second strategy for improving grain alignment and achieving high current density in a wire is to texture a flexible metal strip or its covering oxide layer, and then epitaxially deposit the superconductor onto it. Once that so-called coated conductor or second-generation wire is mass produced, it could enable HTS wire operating at 77 K to have a price/performance ratio (price/kA-m) at or even below that of conventional copper wire found in power equipment.

Superconducting blocks grown as single crystals from a liquid flux have their own set of applications. Magnetic flux pinning in currently available centimeter-sized blocks can be strong enough to trap magnetic fields as large as 17 T at 29 K,[7] and the resulting superstrong magnets can be used, for example, as levitation devices for low-friction magnetic bearings in flywheels.

Figure 2. HTS wires. First-generation commercially available HTS wires are a composite of silver or silver alloy and filaments of $Bi_{1.8}Pb_{0.3}Sr_2Ca_2Cu_3O_{10}$, or BSCCO-2223. (Courtesy of American Superconductor Corp.)

Power applications

The greatest commercial opportunity for HTSs is in electric power applications that require long lengths of wire. Such applications include cables, motors, generators, synchronous condensers, transformers, and fault-current limiters. (See reference 8 and PHYSICS TODAY, March 1996, page 48.)

Among the most advanced of the HTS applications are AC transmission and distribution cables. They have been successfully demonstrated in China, Denmark, Japan, Mexico, and the US, and increased sophistication, performance, voltage level, and length are on the way. One of the most technically sophisticated HTS cables is the Sumitomo Electric Industries/Tokyo Electric Power Co 100-m, cold-dielectric, 66-kV cable, which passed a year-long trial at the Central Research Institute of Electric Power Industry's testing facility in Yokosuka, Japan. As shown in the inset of figure 3, the cable uses three cores for the three phases of electric power. Last month, at the Yokosuka facility, Furukawa Electric concluded its tests of an even longer, 500-m, 77-kV, single-phase cable (see figure 3). Ultimately, much longer cables will be fabricated by splicing kilometer-length pieces together. A Department of Energy–sponsored collaboration among American Superconductor Corp, Nexans, and Air Liquide is building what will be the first permanent HTS cable in a power grid: Their 660-m, 138-kV cable is slated to connect with the Long Island Power Authority grid in early 2006. IGC SuperPower and Southwire Co are leading other US cable projects. (For more about the grid and its future, see the article by Clark Gellings and Kurt Yeager, PHYSICS TODAY, December 2004, page 45.)

Although improved efficiency in transporting energy is an important feature of HTS cables, a stronger commercial driver is their current capacity, which is much higher than that of conventional cables of the same diameter. Wires fabricated from HTSs can support a root mean square current density of better than 100 A/mm^2, a factor of 100 greater than the rms current density typically carried in the copper wires used in transmission cables. HTS cable with additional dielectric, cryostat, and structural layers can transport 2 to 5 times the power of a conventional cable in a given duct and can sometimes be retrofitted to existing ducts. Moreover, HTS cable does not dissipate heat into its surroundings. In urban areas with a plethora of underground communication cables, electrical wiring, and water and sewer ducts, enhanced power throughput coupled with minimal environmental disturbance is a major benefit. In addition to increased power transmission, the HTS current-density advantages could allow transformers to be lighter and more compact, benefits particularly useful for mobile systems such as trains.

The power grid must be able to withstand fault currents, that is, current surges from a short to ground. To protect the grid, circuit breakers are designed to open within a few tenths of a second, and some can carry as much as 80 000 A for that brief interval. But as power sources have been added to expanding grids, fault currents have increased and demand for fault-current limiters has grown.

The resistive current limiter design is one approach to addressing the problem of ever-increasing fault currents. It takes advantage of the fact that, above a critical current, superconductors switch from the superconducting to the normal, resistive state. A variety of resistive HTS fault-current limiters have been and are being built by ABB, ACCEL Instruments GmbH, IGC SuperPower, Siemens AG, and others. ACCEL is currently testing a 10-kV, 10-kA prototype in the RWE grid in Germany.

Rotating machinery, such as that shown in figure 4, represents another relatively advanced area of HTS power application, which is being explored by American Superconductor, General Electric Co, Rockwell Automation Inc, and Siemens.[9] General Electric, for example, is working on a 100-MW utility generator. American Superconductor is developing a 36.5-MW (about 50 000 hp) ship propulsion motor for a future US Navy destroyer platform; a smaller 5-MW motor has passed factory and laboratory tests. The low HTS losses allow the 5-MW machine to function with off-the-shelf cryocoolers that consume minimal energy.

HTS rotating machinery offers several advantages over conventional designs. Net losses, including refrigeration losses, can be cut by about a factor of two when compared to already efficient conventional motors and generators. The higher magnetic fields of HTS rotor coils allow HTS motors to generate higher shear stress across the interface between the rotor and the armature. As a result, HTS designs may be particularly compact and lightweight. For example, American Superconductor's 36.5-MW HTS ship propulsion motor has been designed to have ⅕ the weight and volume of a corresponding conventional motor. Ship architects will be able to take advantage of that compactness to introduce new hulls that offer better cargo and passenger space and improved vessel speed and maneuverability.

Righting the grid

A surprising offshoot of HTS rotating machinery is the dynamic synchronous condenser, essentially a rotating machine like a generator but without an external mechanical energy source driving the rotor. It provides out-of-phase currents to the power grid.

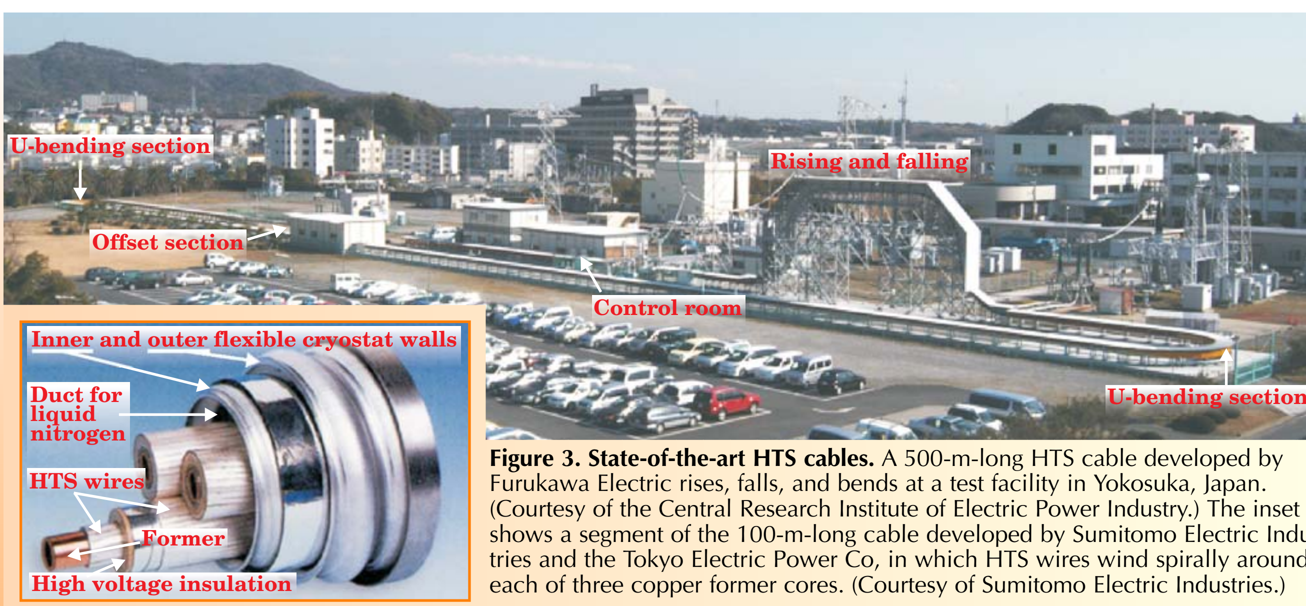

Figure 3. State-of-the-art HTS cables. A 500-m-long HTS cable developed by Furukawa Electric rises, falls, and bends at a test facility in Yokosuka, Japan. (Courtesy of the Central Research Institute of Electric Power Industry.) The inset shows a segment of the 100-m-long cable developed by Sumitomo Electric Industries and the Tokyo Electric Power Co, in which HTS wires wind spirally around each of three copper former cores. (Courtesy of Sumitomo Electric Industries.)

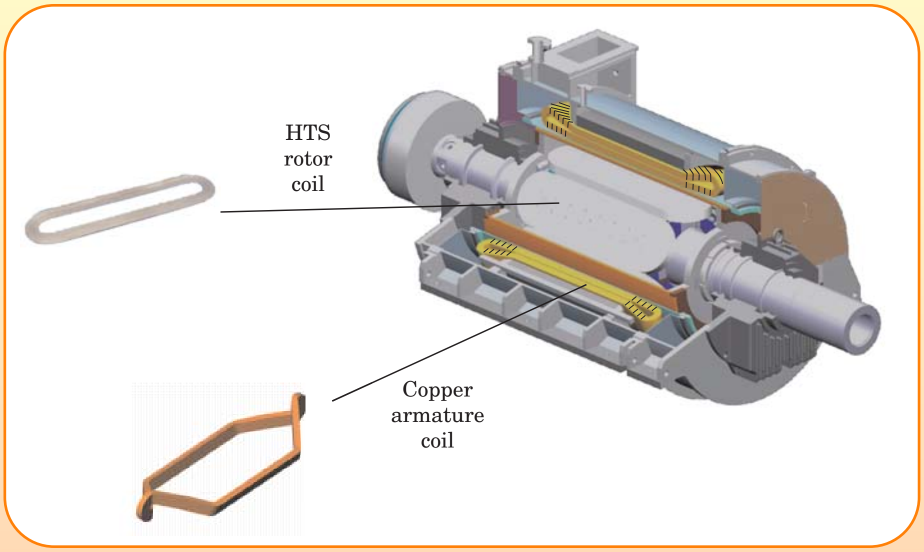

Figure 4. Rotating machines. This schematic shows a cutaway view of a rotating machine with HTS rotor and copper armature coils. The rotor coils are cooled by helium gas or liquid neon. Racetrack-shaped rotor coils are made of HTS wire that operates at around 30 K and 2 T. The armature coils connect to the outside electrical circuit. Like the rotor coils, they are racetrack-shaped. The armature coils, though, have a more complex nested configuration; they face the rotor coils around the cylindrical periphery of the rotor.

The problem addressed by the synchronous condenser may be understood with the help of the simple R–X circuit illustrated in figure 5. An AC source with rms voltage V_0 and frequency ω couples to a resistive load R through a reactance X, assumed to be primarily inductive, that represents transmission lines, transformers, or other elements in a grid. The resulting rms current I has real (in-phase) and imaginary (out-of-phase) components:

$$I = \frac{V_0}{R + iX} = I_0\,(\cos\theta - i\sin\theta),$$

where $I_0 = V_0/\sqrt{R^2 + X^2}$ and $\cos\theta = R/\sqrt{R^2 + X^2}$. The in-phase component determines the average real power transmitted to the load: $P = V_0 I_0 \cos\theta$. Electrical power engineers also speak of an imaginary or volt-amp-reactive (VAR) power $Q = V_0 I_0 \sin\theta$, which arises from the out-of-phase current component. For inductive reactances, Q describes the average rate at which magnetic energy is absorbed from and then returned to the source during each cycle.

Imaginary power plays an important role in determining stress on the grid. The minimum current required to deliver a given real power to a load corresponds to a vanishing phase $\theta = 0$ and hence a vanishing imaginary power. As θ increases, additional current is required to deliver the same power to the load. Furthermore, when lots of people simultaneously demand power, their many parallel resistive loads combine to reduce the net load resistance R.

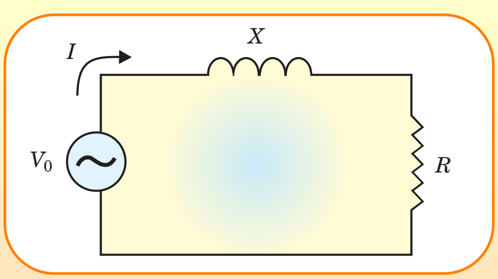

Figure 5. A model circuit. An AC voltage source V_0 generating a current I through a resistance R and inductor X models important features of transmission in the electric power grid.

As a consequence, the current and voltage drop both increase across the inductive reactance X. At the same time, the voltage drop across the load decreases until, once it is below a critical value, the system becomes unstable and the voltage collapses. Such a collapse was a critical element in the chain of events leading to the 14 August 2003 blackout.

For inductive reactances, the current lags behind the voltage. But current leads voltage for capacitive reactances, and so the timely introduction of capacitive elements can prevent or significantly mitigate voltage collapse. Such dynamic VAR compensation is a critical need of the US power grid today. System operators employ a number of conventional methods for VAR compensation, but the HTS dynamic synchronous condenser promises to bring many advantages to the task. Those include large imaginary power output, high efficiency, rapid dynamic response, wide dynamic range, a minimum of switching transients, and long-term reliability from the stable operating temperature of the HTS coils.

To understand the HTS condenser's remarkable capabilities, visualize a C-shaped magnet wrapped with a winding of n turns carrying current I. The flux induced in the gap is proportional to nI and inversely proportional to the gap length. The magnetic circuit of a conventional motor includes iron teeth, in both rotor and armature, that are closely spaced so as to minimize the gap and enhance the flux. A machine with HTS rotor coils and no iron teeth has a much larger effective gap between the armature coils and the magnetic components in the rotor core. Nevertheless, because the high-current-density HTS wire is so fine, a large number of turns can fit onto rotor coils, which enables the HTS machine to generate a greater flux across the gap than does its conventional counterpart.

As the DC HTS rotor coils spin, they generate a time-varying flux ϕ that induces an rms excitation voltage V_e in the stationary armature coils according to Faraday's law $V = -d\phi/dt$. The AC armature current I_a induces in the armature coils a back electromotive force that is proportional to, and out of phase from, I_a and that acts in addition to the excitation voltage. The proportionality constant X_s, called the synchronous reactance, is several times lower than in conventional machines because of the HTS machine's relatively large magnetic gap. The sum of the two voltages induced in the armature coils must equal the grid voltage V_g at the armature coil terminations, so the out-of-phase reactive armature current coupled to the grid is given by

$$I_a = \frac{V_e - V_g}{X_s}.$$

This simple formula has remarkable consequences. If the grid voltage drops below the level set by V_e, the HTS synchronous condenser will inject, essentially instantaneously, capacitive current into the grid—and lots of it, since X_s is small. If V_g climbs above V_e, the condenser injects inductive current. Moreover, one can adjust V_e in a matter of seconds by changing the HTS rotor coil current. That control over V_e allows for a dynamic response to the VAR-compensation needs of the grid.

Figure 6. Protection from voltage instabilities in the power grid. A dynamic synchronous condenser compact enough to fit in a trailer is currently being tested in part of the Tennessee Valley Authority grid. (Courtesy of American Superconductor Corp.)

Using first-generation HTS wire, American Superconductor has manufactured a dynamic synchronous condenser now being tested in the Tennessee Valley Authority (TVA) grid.[9] The condenser can deliver 8 MVAR of imaginary power, both inductive and capacitive. In addition, it is compact enough to fit in a trailer (see figure 6) and so can operate at substations as needed. A TVA order for five additional dynamic synchronous condensers, conditioned upon the successful performance of the prototype, is the world's first commercial order for HTS power equipment.

Filters for wireless communication

Mobile-phone users transmit a microwave signal to an antenna at a base station set up by the wireless company. Because mobile phones typically have limited power, 200 mW or less, the wireless companies have to arrange many base stations on a grid if they are to cover a large area. The grid divides the service region into cells, so one speaks of a network of cellular base stations and cell-phone users.

The increasing demand for wireless communication presents a significant opportunity for the commercial application of HTS materials: Thin-film superconducting filters combined with cryogenically cooled, low-noise semiconductor amplifiers in cell-phone base stations can provide enhanced network coverage and capacity.[10]

As illustrated in figure 7, the base station's HTS filter sits between the antenna and a receiver that further amplifies the signal and extracts its information content. The ideal filter is highly selective in frequency; the illustrated filter transmits only in a narrow passband from 833 to 850 MHz. The transmission performance plots shown in the figure compare a typical normal-metal filter and an HTS filter, and illustrate the superconducting filter's superior selectivity. One reason improved sensitivity is important is that the amplifiers and signal processors are nonlinear and can mix signals that lie outside the desired band; the mixing generates signals with frequencies that appear as in-band noise.

To achieve the improved filter performance, high-quality epitaxial films of YBCO have been grown on 500-μm thick dielectric substrates. The films have a low surface resistance and a high value for another important film property, the so-called intermodulation current density J_I. The parameter J_I characterizes the nonlinear response of the filter—specifically, the degree by which a superconducting current density J reduces the local density n_s of superconducting charge carriers.[11] For the cryogenic temperatures T at which HTS filters operate, $n_s(T, J) = n_s(T)\,[1 - (J/J_I)^2]$. Since the penetration depth varies as $n_s^{-1/2}$, the microstrip's effective inductance contains a small nonlinear correction proportional to $(J/J_I)^2$. Multicrystalline films with weak links can have significantly smaller J_I values than those of epitaxial, highly crystalline films.

Highly selective filters require a large number of coupled resonators. Such construction is possible because of the low loss of HTS films. The Superconducting Technologies filter shown in figure 7 has 10 weakly coupled microstrips, each consisting of a 200-μm-wide folded HTS strip separated from an HTS ground plane by a 500-μm-thick magnesium oxide layer. The oxide has a dielectric constant of about 10; as a consequence, a half-wavelength resonator at 850 MHz is 5.6 cm long. One can obtain a compact filter by folding the microstrips as shown in the figure. The low operating temperature of the HTS filter contributes to its impressive performance. In addition, the cryogenic environment enables one to add a cooled low-noise semiconductor amplifier whose gain raises the signal level and effectively eliminates any problems from noise added further down the receiver chain.

Josephson devices

Superconductor applications of the class called active electronic devices exploit the Josephson currents that flow across superconducting weak links. One can control the currents by manipulating the phase difference between the superconducting states on the two sides of the link and can thereby construct detectors, switches, and calibration standards that run at extremely high frequencies with minute dissipation and very low noise.[12] The SQUID is an example.

No one, however, could fabricate a useful Josephson junction in the first several years after the discovery of HTSs. Scientists understood that the underlying problems resulted from the cuprates' basic chemical and physical

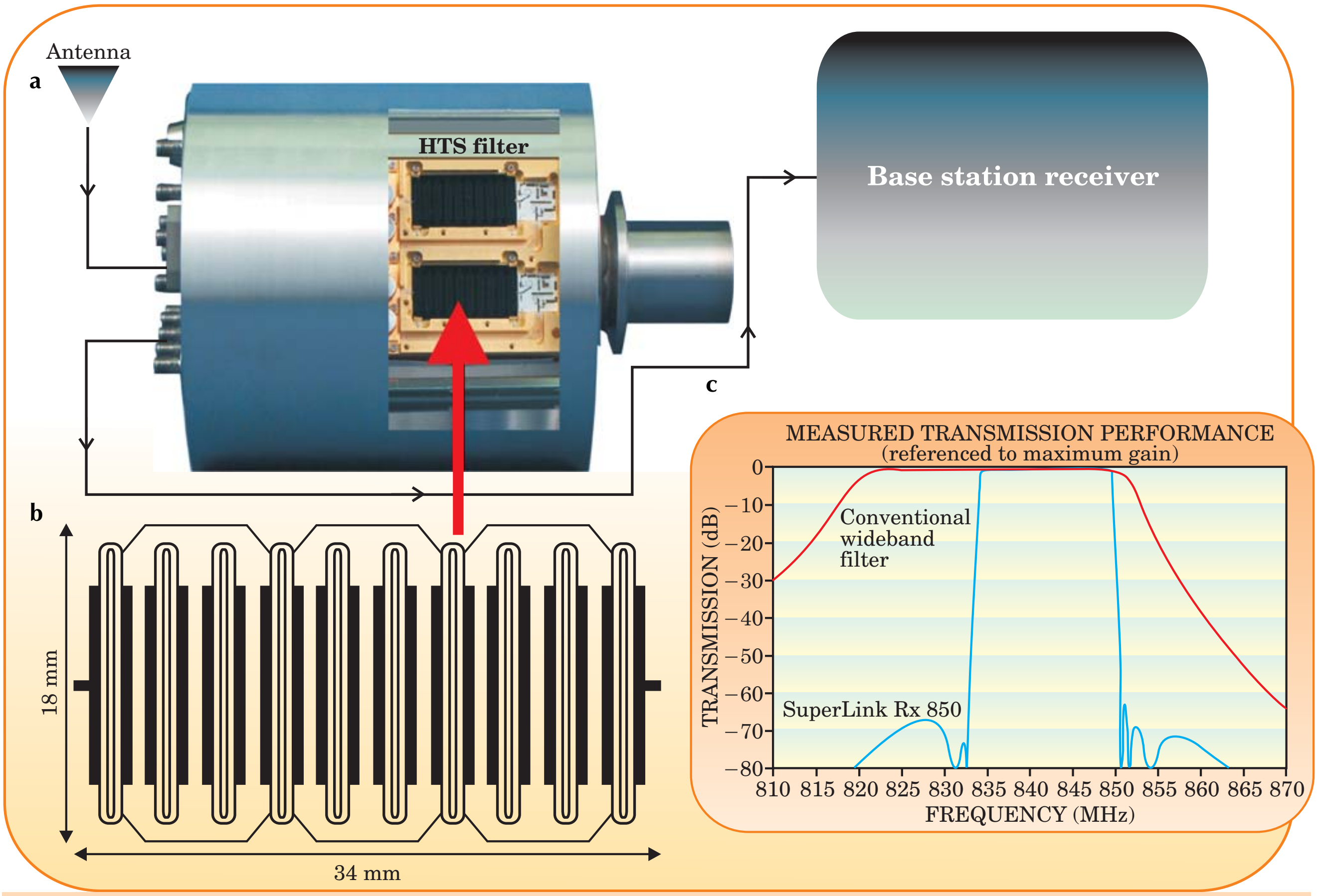

Figure 7. Improved wireless communication. Some 4000 HTS filters are currently in use at wireless base stations in the US. **(a)** The filters (black) sit in a cryogenic chamber between the station's antenna and receiver. **(b)** The filter shown incorporates 10 folded, weakly coupled HTS strips. **(c)** A plot of signal transmission versus frequency demonstrates the enhanced selectivity of the HTS filter over that of a conventional normal-metal filter. (Courtesy of Superconducting Technologies Inc.)

properties. For example, the small coherence length and the resulting susceptibility of the superconductors to defects posed a fundamental challenge. In addition, the motion of stray magnetic flux quanta induced unacceptable electronic noise in early superconducting films. Yet another challenge was related to the superconducting energy gap: A good Josephson junction requires the superconductor abutting the junction's interface to have a large energy gap. But that gap is reduced if the superconductor is chemically or structurally disturbed close to the interface.

As difficult as those problems seemed, they have been partially solved or circumvented. Several electronic applications have been realized that, 15 years ago, would have sounded like science fiction. How did fiction become reality?

First, HTS materials have a large enough energy gap that, for most applications, the gap reduction at a junction can be tolerated. Second, condensed matter scientists learned about the subtleties of the epitaxial growth of complex oxides. That knowledge led to remarkable technical progress in HTS epitaxy: Today, excellent low-noise films that have diameters up to 20 cm are commercially available on many substrate materials. Third, the cuprates, unlike metallic low-temperature superconducting materials, have strong electron correlations, large anisotropy, and a tunable carrier density of about $5 \times 10^{21}/\text{cm}^3$. Such differences opened up unforeseen opportunities. For example, HTS materials can be fabricated with novel Josephson junctions such as bicrystal and step-edge junctions—viable alternatives to the planar structures that are important for low-temperature superconductor technology.

Now it's almost routine to combine HTS materials with optimized noise-rejection schemes and build robust, low-noise SQUIDs.[13] Today's SQUIDs can achieve a white noise level as low as $10\ \text{fT}/\sqrt{\text{Hz}}$ at 77 K, which only marginally exceeds the noise of commercial niobium-based SQUIDs operating at 4.2 K.

SQUIDs promise to play a role in a number of commercial applications. They can measure, with good spatial resolution, the magnetic fields generated by heart currents and so have proved beneficial to cardiographers. In a rather different commercial application pioneered by Tristan Technologies and Australia's Commonwealth Scientific and Industrial Research Organisation, a SQUID forms part of an airborne magnetometer system that locates mineral deposits or buried unexploded ordnance by mapping magnetic anomalies.[14] Such in-flight operation, which requires robust cryogenics and noise rejection, is a demanding task. SQUID-based sensors also offer excellent performance in magnetic-field microscopes, and commercial systems are on the market. Emerging applications include biomagnetism, nondestructive evaluation, and magnetometry, for which novel quantum interference filters can give absolute field measurements.

In ongoing work, researchers are using large numbers of HTS Josephson junctions for digital electronics.[12] The main fabrication challenge is to build numerous junctions with consistent properties. Several groups, though, have reported encouraging results. The Research Center Jülich in Germany has successfully fabricated voltage standards comprising more than 1700 junctions, and the University of Twente in the Netherlands has operated a small multijunction analog–digital converter at 175 GHz. In principle, the intrinsic Josephson junctions between copper–oxygen planes allow for voltage standards with tens of thousands of junctions connected in series. As a final example, scientists from Twente and IBM Research have collaborated on exploratory arrays of YBCO–Nb rings that take advantage of d-wave symmetry and contain 150 000 operating junctions on a chip.

HTS magnet applications are also beginning to make commercial inroads. For example, Quantum Design in San Diego, California, recently announced an option for a physical property measurement system based on a liquid-nitrogen-cooled, transverse-field magnet supplied by the New Zealand company HTS-110. The system also uses commercially available HTS current leads.

Nearly two decades have spanned the discovery of HTSs and the fruitful application of these remarkable substances. That time frame is typical of other complex new materials such as optical fibers or III–V semiconductors such as gallium arsenide. The maturation of HTS technology has required dedicated and sustained efforts by materials scientists, physicists, chemists, electrical and mechanical engineers, and wire and equipment manufacturers. At times, HTS commercialization seemed beyond reach. Today, however, these complex materials are poised to address major markets with real applications that are almost as surprising and unexpected as the initial discovery of HTSs.

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