Superconducting Microwave Filter Systems for Cellular Telephone Base Stations

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Invited Paper

In the second decade following the discovery of high-temperature superconductivity (HTS), wireless communications has emerged as the earliest large commercial market. The enormous growth of the wireless industry coupled with its increasing technology demands has created a significant opportunity for HTS technology in wireless base stations. These systems combine high-performance HTS RF filters with cryocooled semiconductor preamplifiers to offer enhanced sensitivity to improve signal reception and exceptional selectivity to reject interfering signals. There are now thousands of installed HTS systems and the prospects are good for widespread future deployment.

This paper discusses the underlying technologies that support HTS wireless applications, based upon the characteristic microwave properties of HTS thin films and substrates. HTS filter design technology has been under development for a decade and has gained a fair measure of maturity in terms of design tools, simulation techniques, and available topologies. The need for extremely narrow-band filters, highly selective filters, frequency-agile filters, and very compact filter designs has led to many technology advances. On the system level, comparable advances in cryocooler technology and cryopackaging have enabled the development of a broadly deployable technology. We discuss industry trends and the methodologies and results of simulations and real-world measurements of HTS filter systems.

Keywords*—*Cellular front ends, high-temperature superconductivity (HTS) applications, microwave filters, superconductors.

I. Introduction

Superconductivity was discovered in 1911 by the Dutch physicist H. K. Onnes. He observed that below a temperature of about 4 K, mercury metal exhibited perfect electrical conductivity; a direct current could flow with no resistance whatsoever. This hallmark zero-resistance property occurs only at zero frequency, whereas at any finite frequency, superconductors exhibit losses that increase with frequency. But despite this departure from perfection, superconductors nevertheless offer significant performance advantages over conventional materials in microwave circuits, which have, therefore, become some of the most promising applications for superconductive technology.

Superconductors are attractive for use in passive microwave circuits for several reasons. First and foremost is their very low surface resistance in comparison to even the best conducting normal metals. For example, the high-temperature superconductors being used in microwave applications exhibit a surface resistance at 1 GHz that is three to four orders of magnitude lower than that of copper under equivalent conditions (i.e., at 77 K). This performance results in microwave components with negligible insertion losses and in compact resonant structures with extraordinarily high-quality factors.

An advantage of superconductors is that their low-loss properties enable the fabrication of a variety of microwave components in a far more compact geometry than is practical using conventional materials. For example, superconducting delay lines can be far more compact than their normal-metal counterparts. For microwave filters, bulky cavity resonators and dielectric resonator structures can be replaced with compact microstrip designs fabricated on wafer substrates.

The microwave properties of superconductors have been well-known for decades but their use in most applications was precluded by the cost and complexity associated with low-temperature operation. Apart from cavity resonators for particle accelerators and similar exotic applications, there were few opportunities for practical use of superconducting passive microwave circuits until the discovery of high-temperature superconductivity (HTS). The availability of superconductors with critical temperatures above 77 K beginning in 1987 opened the door to cooling superconducting devices with liquid nitrogen or with relatively simple, relatively low-

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cost mechanical refrigerators. This change in the economics of microwave superconductivity enabled the development of a viable industrial technology.

Since the late 1980s, there has been continuous development of the materials, device and system technologies required to support microwave products based on high-temperature superconductors. The better part of a decade was spent in developing the underlying technology that could support a variety of applications; by the mid-1990s, several small companies began to devote their entire efforts to applications for the wireless industry because it was clearly the most attractive opportunity for widespread commercialization. The performance advantages inherent in superconducting filters combined with cryogenically cooled low-noise amplifiers justified a single application focus for these companies. That focus has now resulted in the beginnings of a significant industry, as superconducting products are being deployed in a growing number of cellular base stations around the world.

II. HTS Thin Films and Substrates

HTS filters for the wireless industry have primarily been fabricated using thin films and microstrip technology. HTS filters based on thick-film technology have also been used in commercial applications, but thin-film designs have come to dominate the new industry.

A. HTS Thin-Film and Substrate Properties

The commercial use of HTS thin films for filter applications requires homogeneous, large-area, double-sided films with low surface resistance deposited upon wafer substrates with acceptable microwave properties. The two HTS materials that have been developed to meet these needs for filter production are $YBa_2Cu_3O_{7-\delta}$ (YBCO) and $Tl_2Ba_2CaCu_2O_8$ (TBCCO). YBCO generally crystallizes in a slightly oxygen-deficient form with δ in the formula often around 0.2.

Both of these materials are complex layered compounds whose superconducting properties are highly dependent upon their crystalline structure. In both cases, only epitaxial, c-axis-normal films exhibit the low RF losses required for use in filters. To achieve the epitaxial growth, wafer substrates with suitable crystal structures are required. But in addition to their structural properties, substrates must have a low microwave loss tangent, not react chemically with the superconducting films, have a tolerable thermal expansion match with the films, and have acceptable mechanical properties.

A wide variety of substrate materials has been investigated for use in HTS RF devices, and only three have seen any broad utilization: $LaAlO_3$, MgO, and sapphire. Each of these has drawbacks. $LaAlO_3$ is expensive and undergoes a structural phase transition under thermal cycling that leads to local variations of the dielectric constant. MgO is also expensive and is not very robust mechanically. Sapphire has an anisotropic dielectric constant and, more significantly, has a poor thermal expansion match to the films, which limits the thickness of HTS depositions before thermally induced stresses induce film cracking. To date, MgO has seen the most widespread use in commercial filter systems.

There is continued interest in the use of sapphire as a substrate for HTS filters because it is considerably less expensive than the substrates currently in use, is mechanically very robust and is available in large sizes. If progress continues in developing a reliable process for its use, then sapphire is likely to be widely employed as a substrate. Similarly, if the microwave properties of HTS films on amorphous or polycrystalline substrates (made using ion-beam-assisted deposition or a similar technique) become good enough, such even lower cost materials will be adopted.

The price and availability of current substrate materials has for the most part dictated the standard wafer size for HTS filter production to be 2 in in diameter. Thus, thin-film fabrication processes have concentrated upon the production of two-sided (i.e., films deposited on both sides of the substrate), 2-in films with good RF properties. As a result of commonly available test procedures, a *de facto* standard emerged for surface resistance measured at 10 GHz and 77 K. An HTS film was early on deemed to be of "device quality" if this value fell below 1 mΩ; modern films typically measure below 250 $\mu\Omega$.

B. HTS Thin-Film Production Methods

1) YBCO: YBCO is unquestionably the most widely studied of the HTS materials, and YBCO films have been produced using a wide range of techniques including sputtering (from elemental sources and ceramic targets), pulsed laser deposition (PLD), metal–organic chemical vapor deposition (MOCVD), and various forms of thermal evaporation. Whereas thermal evaporation has largely been supplanted by alternative techniques in the production of semiconductors, the unique requirements of HTS films have led to the successful adaptation of this technique for their production.

Thermal evaporation is an inherently nondirectional deposition technique, which, therefore, lends itself well to large-area uniform film coverage. The difficult requirements for successful growth of epitaxial YBCO films are the need for high substrate temperature (typically 700–800 °C) and high oxygen ambient pressure. To simultaneously achieve these conditions during a thermal evaporation process, a unique heater concept was developed at the Technical University of Munich, Munich, Germany [1]. The innovation is a rotating substrate platter that serves as a partial vacuum seal for a heated chamber held at elevated oxygen pressure. The platter fills the open end of the chamber, leaving only a very narrow (less than 0.5 mm) slit. This arrangement results in a pressure drop of three orders of magnitude between the oxygen-rich chamber and the rest of the vacuum system. Substrates spend the bulk of their time in the chamber, where they are heated and exposed to oxygen. As the platter rotates, the substrates exit the chamber and are exposed to the flux from evaporation sources for the three metallic constituents of YBCO. As long as oxygen is supplied to the deposited metal atoms within a few tenths of a second, they can form the correct phase of the material. Rotating the platter at a few hundred revolutions per minute accomplishes this in the system.

This reactive coevaporation (RCE) technique was quickly shown to be capable of producing the large-area two-sided films required for filter applications [2]. Based on these results, the technique was developed for commercial production at Conductus [3] and has been in continuous use for that purpose since 1997. Production machines in use to date contain a 10-in substrate platter that holds up to twelve 2-in substrates. A next-generation system under development in 2003 utilizes a vacuum loadlock system and larger platter to greatly increase wafer throughput for higher volume manufacturing. While other deposition techniques are still in use for YBCO deposition, RCE is currently the mainstay of film production for RF applications.

2) TBCCO: Materials with higher transition temperature than YBCO are attractive for microwave applications as they enable the use of smaller cooling systems that may require less input power. Of these higher T_c materials, films of TBCCO in the so-called 2212 phase have been demonstrated to have excellent microwave performance and have $T_c > 105$ K, which allows systems to operate at 77 K or above. Because of this performance, both Superconductor Technologies, Inc. (STI), Sunnyvale, CA and DuPont, Wilmington, DE, have commercially pursued TBCCO films for microwave applications.

In situ growth of TBCCO films in the superconducting phase is impractical because of the extreme volatility of thallium. As a result, TBCCO films are typically grown using two-step processes that consist of a deposition step followed by an annealing step. By far the most common procedure for growing such films requires the deposition of an epitaxial, thallium-free Ba–Ca–Cu–O precursor film using *in situ* techniques similar to those used to grow YBCO. These precursor films are then thallinated by annealing at $\sim$800 °C in the presence of a thallium source.

The process STI has been using, essentially unchanged, since 1995 for all of its commercial products is somewhat different. First, an epitaxial oxide buffer layer is grown *in situ* by PLD using a 248-nm UV laser. The buffer layer, which serves as the growth template for the TBCCO film, is grown in a high-oxygen partial pressure (800–1500 mT) and at high temperatures (700–800 °C). This step is followed by the deposition of a thick amorphous layer of thallium-rich precursor material at room temperature, again by using PLD. The crystallization step requires a high-temperature anneal in ambient oxygen. Finally, the TBCCO wafers are placed in reactor vessels that control the loss of Tl_2O at growth temperature so that the films end up with uniform microstructure and the correct ratio of the constituent elements. The resulting TBCCO thin films have microwave performance that is competitive with the best YBCO films and been used in a variety of applications ranging from biomedical magnetic resonance imaging (MRI) pickup coils to cellular telecommunication receive filters.

C. Structure/Properties Relationships

The relationship between the material properties of HTS films and their electrical performance has been extensively studied over the years as manufacturing processes have been developed. The most attention has been paid to film composition, crystallinity, and morphology and how they affect the microwave properties of the films.

In order to achieve consistent results for YBCO, one has to control film composition to within approximately 1% for each of the metallic constituents. Empirical studies have shown that the best microwave films are not those with the canonical "1-2-3" composition but are in fact slightly off. Optimum recipes are closely guarded secrets of film makers.

With respect to crystalline order, the best microwave films are c-axis-normal epitaxial films that lack any a-axis growth or high-angle grain boundaries of any sort. However, when it comes to surface morphology, the best microwave films are not the smoothest films such as those that one would want for multilayer circuits.

Good microwave films exhibit good dc electrical properties such as a high critical current as well as a reasonably high critical temperature. High RF critical current is essential as well. However, these properties are only necessary but not sufficient requirements for microwave device performance. As a result, apart from direct measurements of microwave resonator quality factor, the tools of the trade are such methods as X-ray diffractometry and atomic force microscopy rather than transport measurements. Nevertheless, with film production of many thousands of wafers each year, the ability to prescreen films for use in filters based on monitoring a combination of materials properties has become well developed.

III. HTS Filters and Fabrication

The first decade of HTS research and development resulted in great improvements in materials properties and especially in the uniformity of those properties. The most recent five years have seen a similar improvement in understanding how to design thin-film HTS filters and in how to improve both the performance and the uniformity of performance for these filters. More recently, there has been significant progress in extending the exceptional performance of HTS fixed-frequency filters to tunable filters. This section outlines the requirements that HTS filter design places on the thin-film fabrication techniques and discusses the approaches to thin-film filter design for the wireless marketplace. Brief discussions of electronically tunable filters and thick-film filters follow.

A. Thin-Film Fabrication Requirements

Fabricating HTS thin-film filters essentially requires the standard processing steps that have been developed for semiconductor chip fabrication. The differences that exist primarily relate to the different die and feature sizes and the unique chemistry of HTS materials. In addition, since HTS filters are basically single-layer devices, the processing steps are greatly simplified to include only photolithography, ion milling, contact metallization, and dicing.

The photolithography requirements for HTS thin-film filters are quite primitive by semiconductor standards. The typical minimum feature size of 2 mils (50 μm) is dramatically larger than the 0.15-μm lithography common in semiconductor fabs. Therefore, state-of-the-art steppers are not needed for HTS filter fabrication. Older technology such as projection aligners would be adequate; however, as outlined in the previous section on HTS thin films, the current technology is limited to 2-in substrates for volume production. This not only puts severe restrictions on the allowable filter die size, but it also puts limitations on the availability of lithography tools that can be used. Therefore, the most common production tool is still the contact aligner. This tool is inexpensive, but requires the most rework and care to make sure that linewidths and edge slopes are reproducibly defined. Because these devices are RF devices whose current mostly flows along the outside edges, care must be taken to maintain a consistent edge slope and minimize edge damage during processing.

The method of choice for pattern definition in HTS thin-film filters remains as ion milling. This is primarily due to the fact that a suitable chemistry combination has not been identified that would permit reactive ion etching of cuprate superconductors. There are wet chemical etches that have been developed, but none have demonstrated the linewidth control necessary to make reproducible high-quality HTS thin-film filters. While ion milling does an adequate job for high-volume production, care must be taken to avoid overheating of the photoresist or the HTS film during the patterning process. In addition, the etch angle has been found to be important for a reproducible process.

Normal-metal contact layers are required for making electrical contact to HTS films because the films themselves are unsuitable for either welding or diffusion processes used to attach wires. Both liftoff and etching approaches to contact metallization have been used in production. It is not clear if either approach has a significant advantage. Generally, the adhesion in both cases is not perfect, but contact annealing, while found to be effective, has found disfavor because it is so time consuming.

Dicing the filter die also uses standard semiconductor equipment, although precautions must be taken not to damage the HTS films during this step. An additional complication is the brittleness of MgO substrates. As a future alternative, sapphire substrates are also difficult to dice because of their hardness.

B. Filter Design Approaches

In the early development of HTS filter design approaches for wireless applications, the two primary driving forces were size and quality factor (Q) [4]. As the technology has matured, power handling has become a third driving force in the design criteria. Most recently, the design methodology has matured enough that a final constraint of reduced sensitivity to manufacturing variations is becoming the driving force for future approaches to filter design. This section discusses the evolution of filter design approaches and how the evolving constraints have been addressed.

Early approaches to filters for wireless applications focused on distributed-element resonators [5]. The immediate advantage of this approach is its large linewidth that maximizes the Q and power handling. The concurrent disadvan-

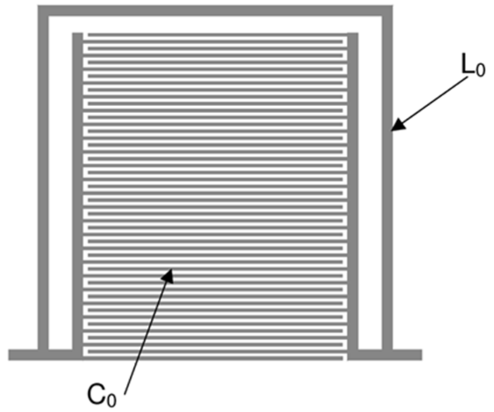

Fig. 1. Geometry of frequency-dependent inductor.

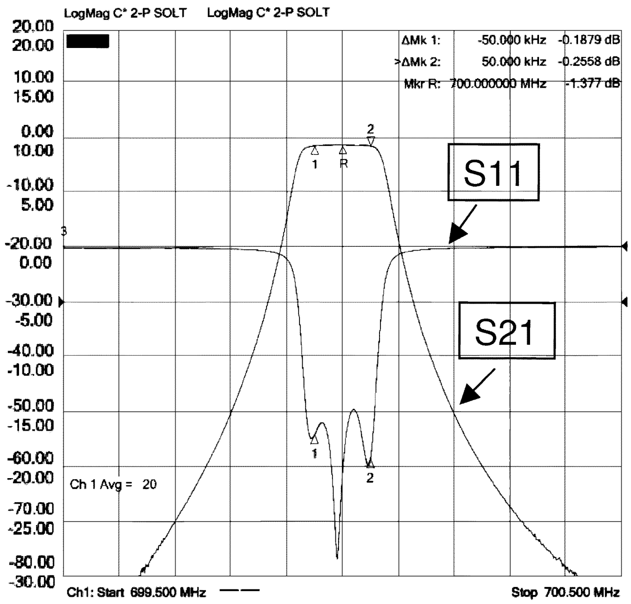

Fig. 2. 100-kHz bandwidth filter, 1 MHz full scale.

tage is the large size dictated by realizing a half-wavelength resonator around 800 MHz. Because of the severe size limitations of available wafer sizes, as well as wafer cost, two approaches were implemented to minimize the die size for a multipole filter. These can be broadly categorized as either the lumped-element resonator approach or the folded half-wavelength resonator approach.

The lumped-element resonator approach leads to the most compact size, especially in the form of the capacitively loaded inductor [6], as in Fig. 1. However, the small linewidths in such a resonator lead to higher sensitivity to manufacturing variations in both linewidth and substrate thickness. Nevertheless, this resonator has successfully been used in both cellular and PCS applications.

This type of resonator has found its strongest application in ultranarrowband filter designs with fractional bandwidths as small as 0.01%. For example, a five-pole lumped-element Chebyshev bandpass filter of center frequency 700 MHz with an equi-ripple bandwith of 100 kHz has been demonstrated using this resonator approach shown in Fig. 2 [7]. There have been many approaches to folding the half-wavelength res-

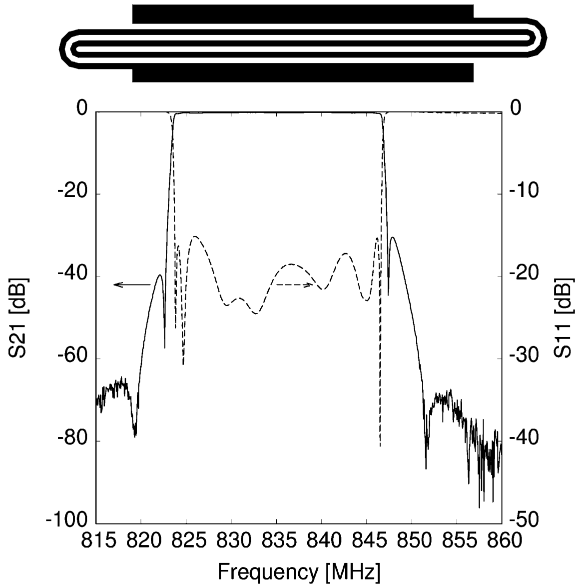

Fig. 3. Geometry of SISO resonator (top) and frequency response of ten-resonator six-transmission zero-SISO filter designed for U.S. cellular A band (bottom).

Fig. 4. Geometry of clip resonator.

onator to maintain the high Q and power handling without needing an excessive amount of wafer space, for example as in [8]. In all of these approaches, the goal was to minimize the radiation, so that the parasitic coupling could be reduced.

We show two examples of approaches to accomplish these goals. The first example is the spiral in/spiral out (SISO) resonator [9]. This resonator has been found to be effective for filter design in both cellular (850 MHz) and personal communications services (PCS) (1.9 GHz) frequency ranges, and has been at the core of STI's SuperFilter and SuperLink products. Fig. 3 shows the geometry of the SISO resonator.

Typical cellular and PCS filters that can be realized with SISO resonators are quasi-elliptic band-pass and band-reject filters with 6–12 resonators and associated transmission zeroes. Two to three such filters can be fabricated on one 2–in MgO substrate. Fig. 3(b) shows the frequency response of a SISO filter designed for the U.S. cellular A band.

A second type of folded half-wave resonator is the clip resonator [10], shown in Fig. 4. This resonator has been used to make extremely high-performance filters for third-generation wireless applications. The clip resonator represents a 54% reduction is required area over a standard hairpin resonator. The folding of the resonator has been optimized to reduce the parasitic coupling to next-nearest neighbor resonators. Fig. 5 shows the measured response from a 22-pole filter designed using the clip resonator. This filter shows better than a 25-dB/100-kHz rejection slope.

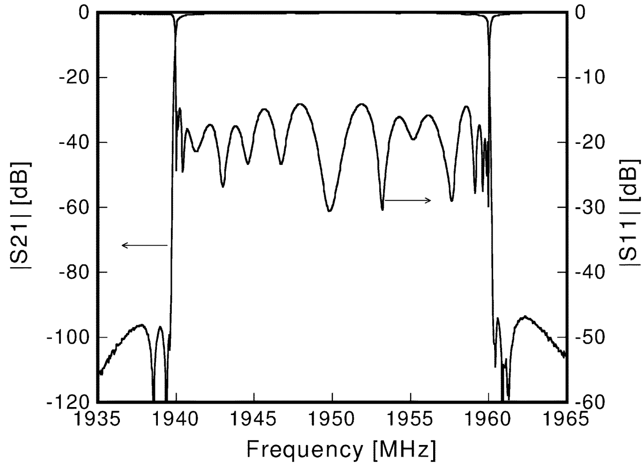

Fig. 5. Measured response of the 22-pole filter [10].

C. Frequency Setting of High-Selectivity Filters

Practical use of the sharp and narrow filters HTS technology enables requires extremely precise adjustment and alignment of the individual resonators that compose the filter. HTS cellular receive filters that are in production today provide rejection slopes of 30 dB/MHz, and filters with ten times higher slopes have been demonstrated. In order to obtain and maintain the desired filter shape, each of the resonators must accurately maintain its specified frequency.

Normal process variations will lead to changes in the frequency response of the filter. The process of optimizing this frequency response, or tuning (sometimes called trimming) the filter, is required to move the filter passband to the desired frequency and to optimize the filter's return loss. Both of these require the resonant frequencies of individual resonators to be able to be adjusted in increments that are much smaller than the filter's bandwidth. As an example, a filter with a maximum 30-dB/MHz rejection will require the resonators to be able to be positioned to better than 30 kHz in order to not degrade the desired filter insertion loss by 1 dB at any given frequency. These requirements can be alleviated somewhat by introducing a small amount of guard band into the filter designs, making the passbands a little bit wider than desired and making the filter rejection steeper to compensate for this. The accuracy required to optimize the return loss depends on the filter order and bandwidth and will often be less than that required by the steepness of the filter's rejection characteristics.

Mechanical tuning elements are used in most high-performance filters. For conventional filters, these are often realized as metal tuning screws. For high-performance HTS filters, this conventional approach would introduce too much loss and degrade the filter shape, so lower-loss alternatives have been devised. STI has used low-loss dielectric tuning elements to tune its production filters. These tuners are typically a sapphire cylinder that is attached to a threaded metal element and behave very much like conventional tuning screws. Another approach that was used at Conductus is to move small pieces of HTS attached to the ends of metal supports above the resonators. Other approaches that do not involve mechanical elements that have been investigated are varactor based tuning and laser trimming.

Once the filter is "on frequency," one has to make sure it stays there. For designs using mechanical tuning elements, the first step is to immobilize the tuners. Next, it is the goal of the system's control electronics to keep the temperature at the HTS circuits constant at the temperature where the frequency response was optimized. The resonant frequency of an HTS resonator varies with temperature primarily due to small changes in the penetration depth of the superconductor. For a wide variety of filter designs, we have found that this effect is typically in the 10–100-kHz/K range and can, thus, be mitigated by a temperature control scheme that can maintain temperatures to better than ± 0.1 K.

D. Electronically Tunable HTS Filters

While fixed-frequency filters are the only current market need for cellular applications, a potential future need is for tunable filters. This need could arise, for example, in various implementations of software-defined radios. There has been significant recent progress on tunable filters for government applications [11], [12], and this technology is making the transition from laboratory technology demonstrations to use in low-volume products.

In order to tune a filter from one frequency to another, either the inductance or the capacitance of its resonators must be changed. Over a moderate tuning range, this is the only change that is necessary. At larger tuning ranges, the interresonator coupling and input/output coupling must also be adjusted [13].

Recent advances in moderate-range filter tuning have focused on using the motion of electromechanical devices to change the resonator inductance. This technique relies on the use of HTS tuning tips (similar to those used to fine-tune fixed-frequency filters) that closely approach the resonator resulting in an inverse power law increase in frequency with tip-resonator spacing. Using this approach, resonator frequency changes approaching 100% have been achieved. However, tuning ranges above 50% require tip-placement accuracy beyond the capability of demonstrated motion-control systems. A wide variety of motors and feedback controls have been explored to achieve reproducible filter tuning over a wide tuning range.

There are two factors that determine the precision with which each resonator of the filter must be tuned. First, the desired accuracy of the tuning with respect to the center frequency of the filter must be used as a criterion. Second, the each resonator's frequency must also be placed accurately enough to give a well-defined filter (good transmission and return loss). Therefore, the bandwidth of the filter has a large impact on the required position accuracy of the tuning tip and, therefore, on the tuning range that can be practically achieved.

E. Thick-Film Filters

Thick-film filters have also been successfully designed and delivered in products for cellular applications [14]. This technology took an early lead in applications because it was easier to achieve superior performance using traditional cavity filter structures and design techniques. However, as thin-film technology has evolved, the advantages of thick-film technology have diminished in receive applications. It is possible that this technology may still find useful application in transmit applications.

IV. Cryogenic Packaging

A variety of cryogenic packaging techniques have been developed for the infrared detector industry, and most of these can be adapted for use in superconducting microwave electronic systems. However, wireless customers expect (and require) long, maintenance-free lifetimes. Thus, one does not have the luxury of routine maintenance such as periodically evacuating dewars or recharging helium in coolers that might be acceptable in other application areas. The cryocooler and dewar, as well as all mechanical parts, must be designed to last for more than 40 000 h of operation, or approximately five years.

Many details of STI's standard commercial rack-mount platform are described in a paper presented the 1996 Applied Superconductivity Conference [15]. Here, we discuss these more generally.

A. Long-Life Dewars and Materials Issues

In order to attain a long dewar lifetime, one must consider two principal factors: vacuum leaks and outgassing of the contents. Reducing the possibility of leakage requires that the dewar be permanently welded shut and also requires careful design of the RF and dc feedthroughs. In order to achieve long life, all feedthroughs must have leak rates of less than 1×10^{-10} cm^3/s He. This far exceeds the levels of hermeticity typically defined for the electronics industry and, thus, often requires custom solutions.

Outgassing can be controlled by the use of appropriate materials and assembly processes within the dewar. The most volatile components (solvents and other organics) can be further reduced by evacuating the dewar at a moderately elevated temperature (typically days to weeks near 100 °C). Higher temperatures could be used to accelerate this process and lead to a lower level of outgassing, but this may lead to degradation of the HTS material. Finally, a getter is incorporated in the dewar to collect any remaining products of outgassing.

B. Cryogenic Microwave Cables

Heat load is another critical consideration in the cryopackaging of HTS filter systems, as these losses determine the size of the cryocooler. A larger cooler is generally undesirable, since it increases the size of the ultimate system as well as the power required to operate it; either factor may rule the system out for a given application.

There are various sources of heat load in a typical cryoelectronic system. A source common to all cryogenic systems is the radiation from ambient, which can be reduced by minimizing the surface area of the cold stage and using high-emissivity radiation shields. A source that is present in

Table 1
Examples of CRFE Cryocoolers

	Heat Lift (W)*	Input Power (W)	Weight (lbs.)	Ambient (°C)
Aisen Seki GM Model GR-101	15	800	79.2	5 to 40
CTI GM Rackmount Cryodyne	9	500	59	5 to 40
Leybold Stirling	6	180	17.7	-40 to 65
STI Stirling	6	100	7.5	-40 to 65

*lift in watts at 77 K, in a room temperature ambient.

most electronic systems is any power that is dissipated in the cold space, e.g., the bias requirements of the low-noise amplifiers in a typical HTS filter system. A source of heat that is particular to RF cryoelectronics is conduction via the RF cables, which can be quite significant.

A pair of cryogenically compatible RF cables, or cryocables, is required to connect each RF circuit to the dewar wall, so that a typical HTS filter system will have 12 or more of these cables. The ideal cable should present a large thermal impedance without introducing significant RF loss. One commonly used approach that has been used by STI and others is to use reduced thickness of the outer conductor of the coaxial cable [16]. Commercially available 0.047-in diameter stainless steel coaxial cable with a reduced thickness outer jacket introduces 0.1 dB of insertion loss with 280 mW of heat load for a 2-in cable. STI's current proprietary cryocables introduce 0.1 dB of insertion loss with 100 mW of heat load for a similar length.

V. Cryogenic Coolers and HTS Filter Systems

A. Cryogenic Coolers

1) Cryogenic Receiver Front-End Cooler Requirements: The advent of HTS filter systems for cellular telephone base stations in the mid-1990s presented cryocooler manufacturers with demanding new requirements not previously addressed. The critical refrigeration requirements were: 1) a minimum of several watts of cooling capacity (heat lift) at the filter operating temperature, between $\sim$60 and $\sim$80 K; 2) operation in ambient temperatures up to 50 °C or higher; 3) little or no maintenance; 4) cost $\ll$\$10 K; and 5) mean time between failures (MTBF) $\gg$100 000 h in continuous operation. Cryocoolers based on the Gifford–McMahon (GM) cycle had an existing commercial manufacturing base and proven reliability and were commonly used in industrial vacuum pump applications. Cryocoolers with small size and high efficiency based on the Stirling cycle were basic to a few then-existing applications, e.g., for spacecraft and for military night vision systems; however, the requirement for extreme reliability at the lowest cost was new. This new requirement led to Stirling cooler developments at several companies, including STI and Leybold [17]. Coolers of both types ultimately made it into commercial use in HTS filter systems. Several are listed in Table 1. As the table shows, the Stirling cycle provides high efficiency, small size, and wide operating temperature range. In the early 1990s, however, it did not offer the proven reliability and commercial manufacturing base of GM designs.

Fig. 6. Photograph of STI Stirling cryocooler.

Table 2
STI Cryocooler Reliability

Infant Mortality	None
Wear-Out Seen to Date	None
Total Number of Coolers:	2,887
Average Hours per Cooler:	9,667
Coolers with > 1 year run-time:	1,342
Coolers with > 2 years run-time:	688
Coolers with > 3 years run-time:	192
Cumulative Hours:	31.3 M
MTBF*:	579,000 hrs

- MTBF based on exponential distribution (# Cum. Hrs / # Fail)

2) STI Cooler Performance: Among the coolers used in cryogenic receiver front ends (CRFEs), one cooler stands out for its performance, reliability, and level of commercial success: the STI cryocooler. The STI cryocooler is a linear, free-piston, Stirling-cycle refrigerator. (Fig. 6 is a photograph of this cooler.) It incorporates gas bearings to eliminate contact between its moving parts. This innovation leads simultaneously to both long life and high efficiency. The cooler has attained an extremely high coefficient of performance for a small cryocooler, equivalent to 1 W of heat lift per 14 W of input power at a cold stage temperature of 80 K in a room-temperature ambient. It has also achieved an extremely low failure rate, equivalent to an MTBF of 597 000 h with more than 31 300 000 h in operation. (See Table 2.) With thousands of units in the field and more than a hundred coolers in continuous operation for more than three years there are no signs of wearout, i.e., reduced lift or wear on moving parts. The manufacturing cost is $<$ \$3000.

B. Commercial HTS Filter Systems

Various turnkey CRFE solutions have been developed around the world. The vast majority of these systems has been manufactured by small U.S. companies and has been marketed directly to their end users—U.S. mobile telephony providers. An essential feature of these systems is to present an external appearance that is not different from most other equipment that is already in a base station, requiring only power and RF connections to be deployed.

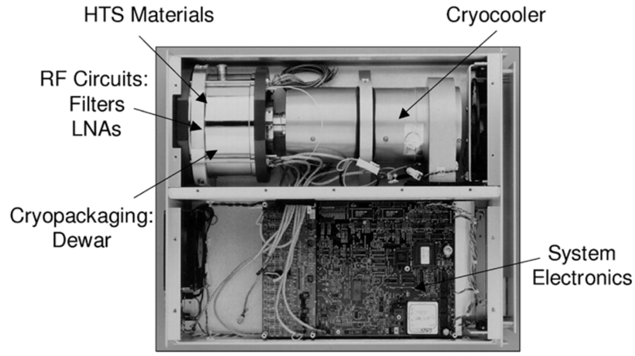

Fig. 7. 1998-vintage STI SuperFilter system with the cover removed highlighting the key technology areas.

Fig. 8. Size comparison of STI SuperLink Rx (2002) (shown on left) and SuperFilter II (1999) (shown on right) product platforms. Both systems contain control circuitry, a cryocooler, and a dewar with six RF paths (HTS filters plus cryo-LNAs).

These turnkey CRFE systems really came of age in late 1996 and early 1997, a period during which four U.S. companies had products on the market (Fig. 7).

During that period Illinois Superconductor (now ISCO International) was selling CRFE systems under the brand names of SpectrumMaster and RangeMaster, the latter including a cryogenically cooled low-noise amplifier (LNA) with their thick-film HTS filters [13]. These systems initially sold well, with ultimately hundreds of systems deployed, but were large and required far more input power than the thin-film solutions provided by the competition.

Also during that time Superconducting Core Technologies (SCT) was marketing its REACH systems. REACH was an ambitious product that sought to include six RF paths, each with thin-film HTS filters and an LNA in a mast-mounted package [18]. In order to keep the size and weight of the tower-mounted portion down, a GM cycle cryocooler was used and the compressor was installed remotely at the base of the tower. Thus, long helium lines were required to connect the tower-mounted-unit with the compressor. Although widely tested by original equipment manufacturers (OEMs) and providers, REACH did not achieve commercial success due in large part to its requirement for long, expensive helium lines going up the tower. SCT ultimately went bankrupt and its assets were acquired by ISCO International.

In late 1996, both Conductus and STI began testing their ClearSite and SuperFilter systems (respectively) with service providers and OEM's. Unlike the REACH system, these products were intended for installation in the equipment rack in the base station, usually found near the base of the tower. Both of these systems were also available with two or six RF paths and were three to five times more compact that ISCO's solutions at that time. Hundreds of ClearSite systems and thousands of SuperFilter systems had been deployed by the time Conductus and STI merged in late 2002.

Also in late 2002, STI released its most compact and lowest power CRFE to date. The SuperLink Rx platform incorporates all of the principal features of the SuperFilter in less than half the size. (see Fig. 8).

C. *Other HTS Filter Systems*

Various other efforts to develop HTS filter systems have existed, but to date these have only produced prototypes and have yet to result in any commercial products. Some of these efforts have taken place within large multinational companies such as LG in Korea, Daikin in Japan [19] and DuPont in the United States [20]. All these organizations have built demonstration systems but none has made it to production.

DuPont has been developing HTS filter systems for satellite applications for many years and ultimately displayed a small tower-mountable system prototype in 2001, but never deployed it commercially.

Other efforts have taken place in smaller companies focused on this application similar to those in the United States. In Japan, Cryodevice Inc. (formerly AMTEL, a collaboration between ALPS and Denso) was actively pursuing HTS filter systems until it was dissolved in 2001. Cryodevice combined advanced filter designs with in-house Stirling and pulse-tube coolers.

In Europe, the efforts to develop HTS filter systems were primarily centered on a consortium of universities and companies involved in the SuCOMS project [21] (GEC-Marconi, Leybold, Thomson, University of Birmingham and the University of Wuppertal). This project developed demonstration systems around the Leybold Stirling-cycle cryocooler. Two smaller companies emerged from this project and continue to pursue the technology they developed under SuCOMS: Cryoelectra GmbH in Germany and CryoSystems Ltd. in the U.K.

VI. Benefits of HTS Filter Systems to Wireless Networks

The HTS filter system or CRFE comprises a very high selectivity, low-loss HTS filter followed by an extremely low noise, cryogenically cooled semiconductor preamplifier. The CRFE circuit connects the base station antenna to the input of the base station receiver. Its purpose is to minimize the degradation of signal-to-noise ratio (SNR) that occurs in the base station receiver as a natural consequence of detecting and extracting the information content of the desired signals. The CRFE accomplishes this by performing two circuit functions extremely well: 1) efficiently and effectively rejecting out-of-band interference and 2) amplifying in-band signals with extremely low added noise and high linearity.

A. Noise and Interference

Receiver noise figure (NF) is the ratio of output SNR to input SNR, when the input noise is equal to a 290-K black body. It is a measure of the linear part of the noise added to the signal by the receiver in the process of extracting the information content, whether voice or data. The noise figure of a receiver, within its band of operation, is independent of time and frequency. It does not include, however, nonlinear effects in the receiver, which add intermodulation distortion products to the signal. The nonlinear response can be complex, but the dominant relevant response for most wireless receivers is captured in the two-tone third-order intermodulation (IMD) intercept point (IP3). Receiver IP3 is measured by introducing two equal-power closely spaced single-frequency tones into the receiver and measuring the output spectrum versus input power. The IP3 is the extrapolated output power at which the power of the primary tones at f1 and f2 equal the power of the third-order IMD products at 2f1–f2 and 2f2–f1. The extrapolation is valid if the IMD products grow 3 dB for each 1-dB increase in the signals at f1 and f2. This is typical for base station receivers, as well as current commercial CRFEs. A typical cellular base station receiver might have a noise figure of 5 dB and an IP3 of -5 dBm. The CRFE provides a means to lower receiver NF to $\sim$1 dB. Receiver IP3 becomes a strong function of frequency: out of band IP3 is dramatically increased thanks to the CRFE's added rejection, while in-band IP3 is degraded due to the CRFE's added gain. This is an acceptable compromise, since the receiver no longer has to handle large out-of-band interfering signals.

1) Base Station Receiver Front Ends: Cellular base station receiver front ends, as installed in the United States today, fall primarily into two categories: broad-filtered front ends that only protect against cellular transmit interference, and selectively filtered front ends that protect against all the principal types of adjacent-band interference: specialized mobile radio (SMR), cellular near–far (interference from nearby mobile units transmitting to distant base stations), and cellular transmit. The insertion loss versus frequency for two commonly used examples of these two types is shown in Fig. 9, along with that of a SuperFilter II. The broad filter is a six-resonator silver-plated combline bandpass filter (BPF) with unloaded resonator Q of 1800. The selective filter is an 11-resonator silver-plated combline BPF with unloaded resonator Q of 3500, in series with a four-resonator dielectric cavity bandreject filter (BRF) with unloaded resonator Q of 17 000. The SuperFilter is a ten-resonator quasi-elliptic BPF in series with a six-resonator quasi-elliptic BRF, both with unloaded resonator Qs of $>$50 000. Fig. 10 shows the noise figures versus frequency for the complete front end of each of these systems, where each preselector filter is followed by a low-noise amplifier. The SuperFilter has both lower noise figure and higher selectivity than either of the other front ends.

In the foregoing, we have compared two commonly used cellular Rx front ends to SuperFilter. There are other front-end architectures used less commonly that provide

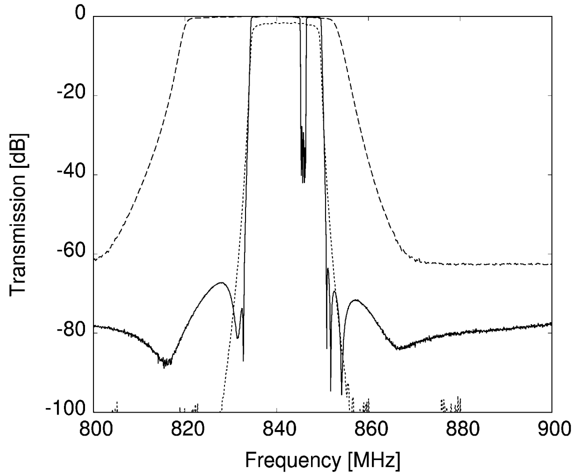

Fig. 9. Plot of insertion loss versus frequency for three cellular base station preselector filters: a common broad filter (dashed line), a common selective filter (dotted line), and SuperFilter II (solid line).

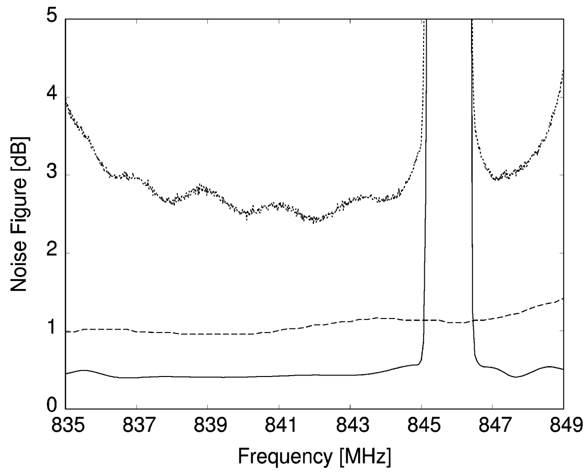

Fig. 10. Plot of in-band noise figure versus frequency for three cellular base station receiver front ends (preselector filters and LNAs): a common low selectivity front end (dashed line), a common high selectivity front end (dotted line) and SuperFilter II (solid line).

better performance, but at higher cost and larger size. These can perform better than the commonly used approaches we have addressed, but they do not perform as well as an HTS filter system, either in selectivity or sensitivity. One approach is to use a dielectric-cavity preselector filter. This provides comparable selectivity to the commonly used selective filter, but lower insertion loss and, thus, lower noise figure. Another approach is to use a broad filter followed with a high-IP3 LNA, followed by a typical selective filter.

2) Adjacent-Band Interference in Cellular Systems: One of the most severe types of adjacent-band interference that arises in cellular systems is from SMR base-station transmissions. In urban and suburban areas of the United States, there are approximately the same numbers of cell sites with SMR as there are with A band or B band cellular (the 800-MHz cellular spectrum in the United States is licensed to two carriers in each geographical region and these spectrum allocations are called the A band and the B band.) We have studied

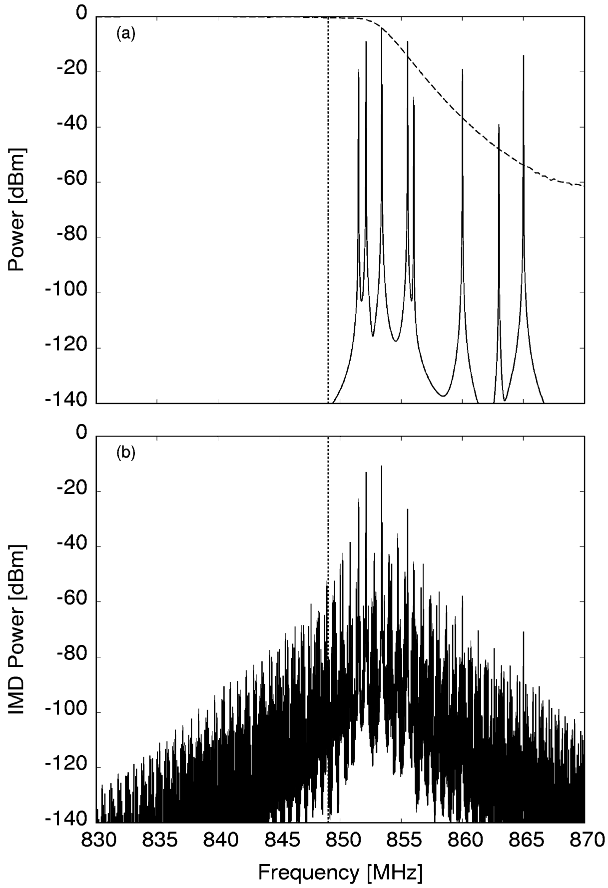

Fig. 11. Plots of: (a) typical SMR spectrum received at an urban cellular base station, overlaid with the insertion loss of a broad filter, and (b) IMD produced in a base station receiver with a broad filtered front end. (Rx IP3 $= -5$ dBm). The vertical dotted line represents the band edge at 849 MHz.

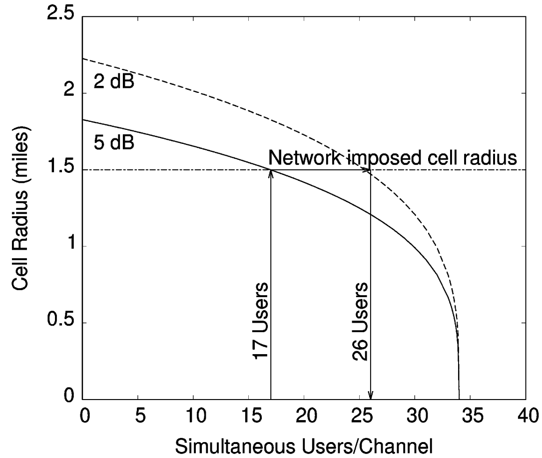

Fig. 12. Overlay plot of CDMA uplink range versus number of simultaneous users for two values of noise figure, 5 and 2 dB. For a fixed cell radius lower NF allows more simultaneous users. (Hata model propagation is assumed [22].)

the levels of interference at cell sites from these sources. Our statistical modeling and field measurements both indicate that approximately half of these sites experience SMR interference powers > -30 dBm, while approximately 10% experience SMR power levels > -10 dBm. In collocated sites these power levels commonly reach > -5 dBm; and in sites that are separated from an SMR site by only a few hundred feet or less, interference levels can reach $+10$ dBm.

Common levels of SMR interference can seriously degrade the uplink in a base station that has a broad filtered front end. Fig. 11 shows an SMR spectrum that might be seen in 10% of urban and suburban sites and the resulting intermodulation power that would be produced in the base station receiver due to this interference. The frequency resolution here is 30 kHz. The typical antenna noise background at this bandwidth is about -130 dBm. Clearly, the effect of the IMD products is to degrade detection of desired signals in the receiver by tens of decibels over much of the cellular B band.

3) Uplink Enhancement Improves Cellular Quality of Service: Improved noise figure in the base station receiver translates into better network performance. For analog and time-domain multiple access (TDMA) digital systems, where the link to each handset can be considered independently, this means simply better coverage for those areas where maximum handset transmit power is insufficient to maintain acceptable SNR at the base station receiver, i.e., increased range, fewer coverage holes, and better in-building coverage. For code-division multiple access (CDMA) digital systems, where all the handsets in a cell and in the same channel share the link, this means that the above benefits are obtained for a specific loading of that channel. In other words, one achieves better coverage or the ability to carry more simultaneous calls. The effects of noise figure on coverage area and usable channel capacity are illustrated in Fig. 12. For a given network imposed cell radius, determined by the existing positions of cell sites, a reduction in SNR permits more simultaneous users. In the specific example shown in the figure, there is a greater than 50% increase in capacity utilization when the NF is reduced by 3 dB. This increase in usable uplink capacity could be less or more depending on various factors, but this is fairly typical for CDMA systems today. From Fig. 12 one can also infer a $\sim$23% uplink range extension from reducing NF from 5 to 2 dB for the case of 17 users. This is similar to what would be achieved in an uplink limited TDMA system for typical propagation conditions.

The practical benefits of HTS filter systems are regularly seen in field trials. Trials usually involve two weeks of network statistics, before and after installing a SuperFilter. Dozens of such trials have been performed in recent years, with very consistent results. Typically the base station receiver noise figure is lowered by 3 dB by the installation of the HTS filter system. The improvement to the uplink is larger due to the selectivity improvement from the HTS filter and from the powering down of handsets in the immediate and nearby cells. A representative HTS filter trial was performed in a U.S. city of 200 000 people. Five 3-sector cell sites covering the center of the city were retrofitted with SuperFilter systems. Concurrently, the nine adjacent sectored sites covering the outer areas of the city were also monitored. The average cell radius in retrofitted sites was 1–2 mi. Each sector of the 15 retrofitted sectors had two

IS-95 CDMA channels, for a total of 30 channels. The outlying sites were also three-sector sites with two CDMA channels in each sector. The spectrum used was cellular B band. Initially all base stations were equipped with broad filtered frontends supplied by the base station manufacturer. All sectors and channels improved. Dropped calls were reduced from an average of 3.0% to 1.7% overall. The range observed was 18.7% to 63.6% reduction over all channels and sectors. The adjacent sectors, without SuperFilters, went from an average of 2.0% to 1.7% dropped call rate. Ineffective attempts went from 3.3% to 2.5%, a 26% average reduction. This type of improvement is fully consistent with the 3-dB improvement in receiver NF from the HTS filter system and the capacity increases shown in Fig. 12 [23], [24]. Increased capacity is difficult to measure in practice and network performance is commonly judged from measured dropped call rates and ineffective attempt rates.

VII. Conclusion

HTS front-end technology is an evolving technology in which new features and enhanced performance continue to be added to the products. The systems are getting more sophisticated and some are now combined with other base station components such as duplexers and power amplifiers. One goal of the HTS industry is to eventually have the technology designed into future base stations, which would be the path to the most widespread deployment. In little more than a decade, high-temperature superconductors have gone from a novel discovery in the laboratory to a technology playing an ever-growing role in the wireless industry. In the 21st century, multiple electronic technologies play a dominant role in society and superconductors are now joining their ranks.

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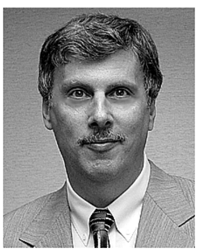

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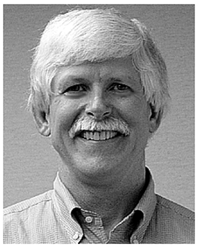

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