Microwave Superconductivity

Raafat R. Mansour, *Fellow IEEE*

Invited Paper

***Abstract*—This paper provides an overview of the microwave applications of high-temperature superconductor (HTS) technology. The main characteristics of HTS materials are outlined, highlighting the differences between superconductors and normal conductors. This paper presents recent progress in the development of HTS filters, multiplexers, cryogenic receivers, delay lines, and antennas. A brief summary of cryocooler technology and cryopackaging requirements is presented. The benefits of using HTS technology in wireless and satellite systems are also discussed. The intent of this paper is to provide perspective to newcomers in the field and to empower the potential end-users with current status and performance capabilities of HTS microwave devices.**

***Index Terms*—Cryogenic receivers, high-temperature superconductors, HTS technology, microwave filters and multiplexers, microwave superconductivity, satellite payloads, wireless base-stations.**

I. Introduction

The Nobel Prize-winning discovery of high-temperature superconductors (HTSs) in 1986 has sparked a worldwide research and development effort over the past 15 years. Although conventional low-temperature metallic superconductors have been known for quite some time, the extremely high cost of refrigeration has limited their use in many applications. The new HTSs allow the use of cooling systems, which are much smaller and less expensive than those required for metallic superconductors.

Superconductors, as opposed to conventional conductors, have the ability to conduct electrical current with very small resistance, no power loss, no generation of heat, and greatly reduced levels of noise. The resistance is very small, but finite at microwave frequencies and truly zero at dc. Superconductivity was first understood as a very low-temperature phenomenon and was explained by Bardeen, Cooper, and Schrieffer in what has become known as the BCS theory. According to this theory, at a particular low temperature, called the transition temperature or critical temperature (Tc), the electrons in certain materials pair up and form a single quantum state, acting like a frictionless fluid and becoming superconducting.

Until 1986, researchers had not identified any materials that could become superconducting with a critical temperature higher than 23 K. The materials discovered up to that time, which had critical temperatures lower than 23 K, were commonly known as low-temperature superconductor (LTS) materials. Since 1986, a new class of ceramic materials that are superconductive at temperatures as high as 125 K has been identified. Referred to as HTS materials, these materials generally have significant advantages over LTS materials because they can be cooled at economically and commercially feasible temperatures.

Superconductivity is certainly a multidisciplinary field. It spans almost the entire realm of electrical engineering, including microwave, power, electronic, and computer engineering. Our focus in this paper is on microwave applications. It is, however, worth mentioning some of the other unique applications of this technology. The list [1] includes electrical transmission cables, motors, generators, fault current limiters, superconductor magnetic energy storage systems (SMESs), magnetic resonance imaging (MRI), and high-speed computing.

In microwave applications, the HTS technology offers major breakthroughs in performance of components and subsystems. Lightweight, small volume, and high performance, which are the properties of the superconducting technology, are also the main drivers in the design and construction of microwave systems. The feasibility of using this technology to design microwave components such as filters, multiplexers, receivers, delay lines, couplers, antennas, and phase shifters with superior performance has been already demonstrated. A review of progress over the past ten years is given in [2]–[4]. Three books have also been published on microwave superconductive devices [5]–[7].

Although the quest for room-temperature superconductor materials goes on, the quality of today's materials is adequate for the development of advanced superconductive systems with a superior RF performance for wireless and space applications, in particular, in wireless base-station applications, where the HTS technology is currently being commercialized by several companies in the U.S., Europe, and Japan.

In this paper, we first provide a brief historical overview summarizing the key development milestones of the technology. We discuss the basic material characteristics, highlighting the unique features that are relevant to microwave applications. We then cover the progress to date in various microwave applications of high-temperature superconductivity.

II. History and Phenomena of Superconductivity

The history of superconductivity can be divided into two eras. The first began with the discovery of the phenomenon in 1911

Manuscript received August 23, 2001.
The author is with the Electrical and Computer Engineering Department, University of Waterloo, Waterloo, ON, Canada N2L 3G1.
Publisher Item Identifier S 0018-9480(02)01982-8.

and lasted for 75 years. The second era starts in 1986 with the discovery of the high-temperature oxide superconductors.

The first era commenced with Onnes, a Dutch physicist, who successfully liquefied helium in the early 20th Century at around 4.2 K. While investigating the effect of such low temperatures on the properties of various metals in 1911, Onnes observed that the ohmic resistance for mercury vanishes at about 4 K. He made the same discovery with lead and tin shortly after. The progress in understanding superconductivity and in developing superconductors with transition temperatures higher than 4 K was agonizingly slow. By switching from single elements to alloys, researchers were eventually able in 1941 to raise the transition temperature to 15 K for niobium nitride. It took, however, over 30 years to further raise the transition temperature to 23 K with the discovery of the niobium–germanium alloy in 1973. A number of systems already use low-temperature superconducting devices. A comprehensive review of the applications of low-temperature superconductivity is given in a January 1973 special issue of the PROCEEDINGS OF THE IEEE. The LTS materials are still being used today in various applications.

It was not until 1957 that a theory finally emerged to give an acceptable microscopic picture explaining why metals become superconductors at low temperatures. Three physicists at the University of Illinois, i.e., Bardeen, Cooper, and Schrieffer, introduced what is now known as the BCS theory, named after the initial letters of their last names. The theory was criticized from the start for failing to provide predictions that match experiments. Numerous revisions and even quite different models were proposed.

The second era commenced in 1986 with the discovery of a new class of superconducting materials with a record-breaking temperature of 35 K by Muller and Bednorz, both of IBM Zürich. The compound was a ceramic with a complex structure: an oxide of lanthanum, barium, and copper. Muller and Bednorz were awarded the 1987 Nobel Prize in physics for their discovery.

Early in 1987, Chu and his colleagues at the University of Houston reported the real breakthrough in HTS, a yttrium–barium–copper–oxide compound (Y–Ba–Cu–O) with a transition temperature of 94 K. The material is commonly known as YBCO material. The new materials operate well at 77 K, allowing the use of liquid nitrogen rather than liquid helium. Liquid nitrogen is much cheaper and denser and has a heat vaporization that is 60 times larger than that of liquid helium. The ability to use liquid nitrogen rather than liquid helium reduces the cost of cooling by a factor of 1200.

In December 1987, Maeda's group at Tsukuba Laboratories, Tsukuba, Japan, reported the bismuth–strontium–calcium–copper–oxides (Bi–Sr–Ca–Cu–O), which began superconducting at 110 K. The next breakthrough was announced in February 1988 at the World Congress on Superconductivity, Houston, TX. Sheng and Hermann from the University of Arkansas reported success with a thallium compound (Ti–Ba–Ca–Cu–O) having a transition temperature of 120 K.

In 1993, Chu's group at the Texas Center for Superconductivity, University of Houston, announced the discovery of a mercury compound HgBaCaCuO having a transition temperature of 161 K. For the first time, superconductors could conceivably be cooled by the household coolant Freon, which exists in liquid form at 147 K. The stability of this compound is still, however, in question since it was developed in a procedure that involves static pressure of 150 thousands of atmospheres. It is believed that chemical substitution may be used to achieve the same result the high pressure is now achieving. Fig. 1 summarizes the history of the superconductor materials.

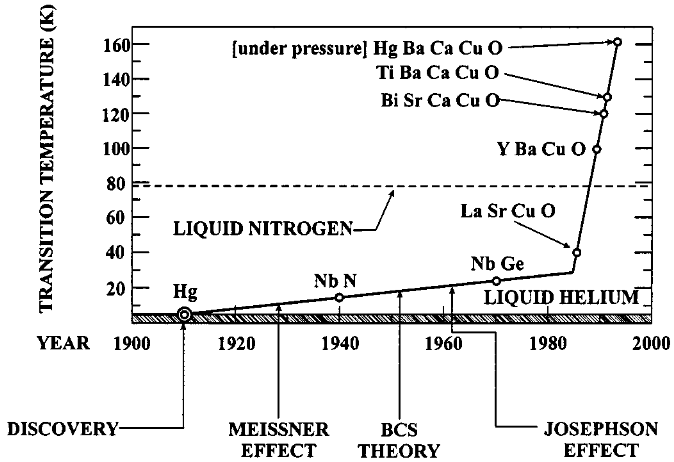

Fig. 1. History of the superconductor materials.

Shortly after the discovery of the YBCO materials at temperature near 90 K, scientists and engineers became very interested in the prospects of employing the HTS technology in the design of microwave components and subsystems. The Naval Research Laboratory (NRL) established a program known as the High Temperature Superconductivity Space Experiment (HTSEE) in 1989. This program was a major catalyst to the development of microwave superconductivity. It consisted of two phases: the focus of the first phase HTSEE-I (1989–1992) was to develop microwave HTS components such as resonators and filters [8], while the focus of the second phase HTSEE-II (1992–1996) was to develop advanced HTS subsystems [9]. Over 30 organizations from the U.S., Canada, and Europe provided devices and subsystems to the HTSSE program [8]–[11]. The results obtained from this comprehensive research program did conclusively demonstrate that viable and robust HTS subsystems could be developed, fabricated, and cryogenically packaged for both ground and space applications [11].

In addition to the HTSSE program, several other focused programs were led by government agencies in the U.S., Japan, Canada, and Europe on advancing the microwave HTS technology. In particular, the U.S. Defence Advanced Research Projects Agency (DARPA), which sponsored several research programs in this field [12].

Another key factor that helped advancing the development of HTS microwave devices was the rapid progress of the wireless industry in the 1990s. Several startup companies emerged in the U.S., Europe, and Japan over the past decade[1][2][3][4] with a focus on

[1]Superconductor Technol. Inc., (STI), Santa Barbara, CA.

[2]Conductus, Sunnyvale, CA.

[3]Illinois Superconductors, Chicago, IL.

[4]Advanced Mobile Telecommunication Technology Inc. (AMTEL), Aichi, Japan.

the commercialization of HTS microwave devices for wireless applications.

III. Characteristics and Theories of Superconductors

Superconductors have unique characteristics that differ from those of normal conductors. Much lower loss can be obtained with superconductors corresponding to lower RF losses. The surface resistance of superconductor materials at microwave frequencies is at least one order of magnitude smaller than that of normal conductors. While the surface resistance of a normal conductor varies with frequency as $(f)^{1/2}$, that of superconductors varies with frequency as $(f)^2$ [7]. This frequency dependence is seen experimentally and can be easily deduced from theory.

Superconductors have a surface resistance that is dependent on the applied field. The dependence is more pronounced at high levels of fields, leading to nonlinearities and generation of intermodulation products. Such nonlinear characteristics have a negative impact on the power-handling capability of microwave superconductive devices [13]–[17]. The same nonlinear characteristics, however, were exploited to develop novel HTS devices such as mixers [7], and nonlinear transmission lines (NLTLs) [18]. Another characteristic of superconductor materials is that they have frequency-independent penetration depth that determines field penetration into the materials rather than the skin depth as for normal conductors.

There are two other unique characteristics of superconductor material, i.e., the Meissner effect and flux quantization. The Meissner effect relates to the superconductor's ability to expel the magnetic field, i.e., superconductors are perfect diamagnets. This characteristic makes it possible to suspend a magnet in midair over a piece of superconductor materials. The Meissner effect also implies that the transition to the superconducting state is sensitive to the magnetic field, and for increasing magnetic fields, the flux first penetrates and then destroys the superconducting state. Correspondingly, a superconducting transmission line can be driven into the normal state by a sufficiently large current, the transition usually occurring sufficiently sharply to define a critical current.

The flux quantization relates to the phenomenon that the magnetic field generated from a current circulating in a superconducting loop is quantized. The unit of quantization is known as the fluxon, or flux quantum, and is given by 2.07×10^{-15} Wb. The characteristic of flux quantization makes it possible to build extremely sensitive magnetometer devices capable of measuring extremely low levels of magnetic fields. Such magnetometers are known as superconductor quantum interference devices (SQUIDs) [19]. Table I summarizes the differences between superconductors and normal conductors.

For microwave applications, the two most important parameters of HTS materials are the surface resistance Rs and the critical current density Jc, which represents the maximum current that can be carried by the superconductor before switching to the normal state. There are several techniques available to measure these two parameters [5]–[7]. The typical values for Rs and J_C for HTS thin films are 100–200 $\mu\Omega$ and 10^6 A/cm^2, respectively.

TABLE I
Differences Between Sperconductors and Normal Conductors

Characteristic	Normal Conductor	Superconductor
Surface resistance at 77 K and f=5 GHz	5 mΩ (Cu)	0.1 m Ω (TBCCO)
Frequency dependence of surface resistance	$(f)^{1/2}$	$(f)^2$
Field dependence of surface resistance*	Constant	$Rs \propto H^2$
Field penetration	Skin depth (δ)	Penetration depth (λ)
Meissner effect	Not applicable	Applicable
Magnetic flux quantization	Not applicable	Applicable

* The dependence on magnetic field H is very weak at low levels of H.

The HTS thin films are deposited on a low-loss dielectric substrate and are processed using standard photolithographic techniques. The most widely used substrate is lanthanum aluminates ($LaALO_3$) with a dielectric constant of $\varepsilon_r = 23.5$ and a loss tangent of $\tan\delta = 3 \times 10^{-5}$. One challenge with the $LaALO_3$ substrate is that its crystal structure exhibits twining, which makes the substrate effectively inhomogeneous. This can affect the ability to set the frequency correctly in narrow-band filter applications. Another commonly used substrate for HTS films is magnesium oxides (MgO) with $\varepsilon_r = 9.7$. MgO does not suffer from twining problems, but on the other hand, it does not offer the same miniaturization that the $LaALO_3$ substrate offers because of its high dielectric constant. Sapphire substrates have also been used with various buffer layers to provide the appropriate lattice match to HTS films. However, the surface resistance Rs and current density Jc are inferior to films on $LaALO_3$ or MgO substrates.

Dielectric materials typically exhibit a considerable improvement in loss tangent $\tan\delta$ upon cooling to cryogenic temperatures. For example, high purity sapphire $(\varepsilon_r = 9.4)$ at X-band frequencies exhibits $\tan\delta$ of 10^{-5} at 300 K and $\tan\delta$ of 10^{-7} at 77 K [20]. MgO and $LaAlO_3$ exhibit a similar loss-tangent improvement at cryogenic temperatures [21] as compared to room-temperature operation. This is considered a fringe benefit of operating at cryogenic temperatures.

The HTS films are deposited on 2- and 3-in wafers, which can vary in substrate thickness from 0.010 to 0.1 in (standard substrate thickness are 0.01 and 0.02 in). The HTS films are typically deposited either by laser ablation or by sputtering techniques [22]. 2- and 3-in wafers with HTS films on one or both surfaces are commercially available from various sources at prices that are almost 1/10 their prices in the early 1990s.

The BCS theory deals with superconductors from a microscopic point-of-view. Two other well-known theories were developed to deal with the macroscopic properties of superconductors, i.e., the London theory [23] and the Ginzburg–Landau (GL) theory [24]. These two theories have been used in conjunction with Maxwell's equation to model the electromagnetic characteristics of superconductive microwave devices

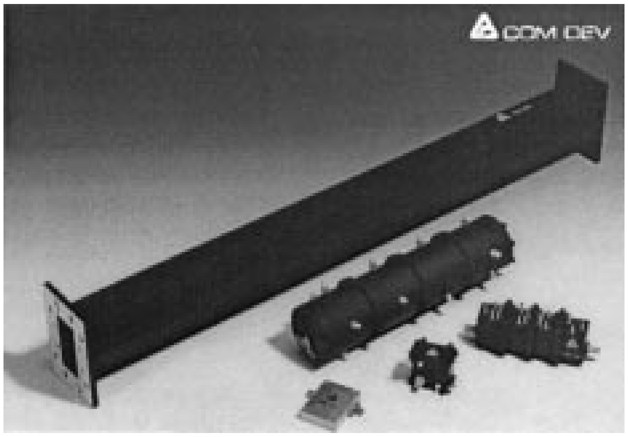

Fig. 2. Comparison between various microwave filters.

[25]–[27]. The London theory is based on the two-fluid model [23], which assumes that the current in the superconductor is carried by normal electrons and superconducting electrons whose densities are a function of temperature. The London theory has been successful in explaining several of the characteristics of superconductor materials. It does not, however, take into consideration the field dependence of the constituent parameters of the superconductor materials. The GL theory, on the other hand, is a more comprehensive macroscopic theory that accounts for field dependence allowing the characterization of the nonlinear behavior of the superconductive materials.

IV. HTS Microwave Filters

Microwave filter networks represent a critical and substantive portion of any communication system. Such a system, be it wireless or satellite, requires filters to separate the signals received into channels for amplification and processing. The phenomenal growth in the telecommunications industry in recent years has brought significant advances in filter technology as new communication systems emerged, demanding equipment miniaturization, while requiring more stringent filter characteristics. The emergence of the HTS technology has offered the possibility, for the first time, to build filters that can compete with traditional waveguide and dielectric resonator (DR) filters not only in size, but also in Q.

Fig. 2 illustrates a pictorial comparison between microwave filters realized using rectangular single-mode waveguide technology, circular dual-mode waveguide technology, DR technology, and superconductor technology [28]. Two types of superconductive filters are included in this figure: one uses the hybrid DR/HTS technology and the other is based on HTS thin-film technology. All filters have the same order and are designed to operate at the same center frequency of 4 GHz. It is clear that a significant reduction in size and mass can be achieved with the use of HTS technology.

In addition to size and mass reduction, HTS filters also offer improvement in the insertion loss. The unloaded Q of a microwave resonator in general can be written as $Qu = (Rs/G + F \tan\delta)^{-1}$, where G is a factor determined by the resonator's geometry, which typically increases as the resonator dimensions increase, while F is a factor determined by the fraction of the electrical energy of the cavity stored in the dielectric materials. Rs is the surface resistance and $\tan\delta$ is the loss tangent of the dielectric material. It is clear that the unloaded Qu can be increased by reducing either Rs or $\tan\delta$ or both of them.

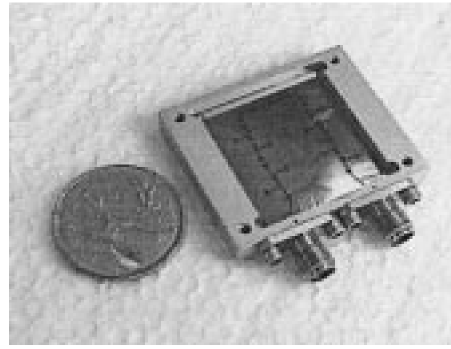

Fig. 3. Ten-pole HTS thin-film filter.

There are three main types of HTS filters reported in the literature as follows:

1) HTS thin-film planar filters;
2) hybrid dielectric/HTS filters;
3) HTS thick-film coated filters.

In both HTS thin-film planar filters and thick-film coated filters, the Q improvement is mainly attributed to the reduction of Rs by replacing normal metals with HTS materials. On the other hand, the improvement in Q in hybrid dielectric/HTS filters is attributed to the reduction of Rs, as well as to the reduction of the loss tangent of the substrate due to cooling.

A. HTS Thin-Film Planar Filters

Planar filters such as stripline, microstrip, and coplanar line filters have been known for over three decades [29]. These filters, however, have very limited applications because of their low-Q values. Effectively, any known planar filter configuration can be realized in HTS technology by replacing metals films with HTS films. This, in turn, would increase the filter Q value by several orders of magnitude. For example, a half-wavelength microstrip resonator made of gold films on lanthanum–aluminate substrate would typically have an unloaded Q value of 400. Replacing the gold films with HTS films while using the same substrate would provide an HTS resonator with an unloaded Q value around 30 000.

The emergence of the HTS technology has created the opportunity for much more innovation in planar filter configurations. Over the past years, several novel filter configurations have been proposed allowing the realization of quite advanced filter functions [30]–[34]. Fig. 3 illustrates a packaged HTS ten-pole elliptic-function self-equalized planar filter. The basic building block of this filter is a dual-mode lumped-element resonator, which makes it easy to create elliptic and self-equalization functions [35].

The emergence of several commercial computer software packages for simulation and design of planar circuits in the early 1990s has played a key role in advancing the development of HTS planar filters. Even though these commercial packages do not take into consideration the physical characteristics of the superconductor materials, they have been successfully used

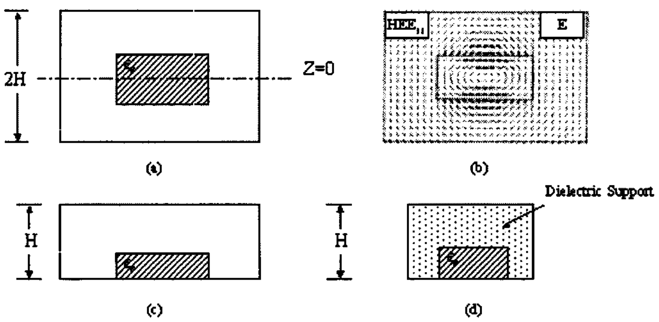

Fig. 4. Transition from conventional DR cavity to an image DR cavity. (a) Conventional DR resonator. (b) Field distribution. (c) Image DR resonator. (d) Image DR resonator with a DR support.

in the design of planar HTS filters, particularly for low-power applications.

B. Hybrid Dielectric/HTS Filters

For the conventional DR shown in Fig. 4(a), the tangential electric field of the HEE_{11} mode vanishes at the plane $z = 0$ [36]. As a consequence, introducing a conducting wall at this plane will slightly perturb the field distribution of this mode. Thus, the size of the DR filter operating in the HEE_{11} mode may be reduced by supporting the resonator directly on a conducting surface (image plate), as shown in Fig. 4(c). With the use of dielectric support that fills the whole cavity, further size reduction can be achieved, as shown in Fig. 4(d).

A normal-conducting image plate, however, significantly degrades the Q of the resonator, which, in turn, makes the approach unfeasible for high-Q applications. On the other hand, if the image plate is replaced by a surface made of HTS materials, the original unloaded resonator Q will be only slightly affected, allowing the use of this resonator structure to realize compact-size filters with a superior loss performance for cryogenic applications [37], [38]. The reduction in size is attributed to the use of the image plate, while the improvement in loss performance is attributed to the use of the HTS image plate, as well as to the increase in the unloaded Q of the DR as the temperature is lowered from 300 to 77 K.

Several hybrid DR/HTS filters, which utilize the concept illustrated in Fig. 4, were built and tested [37], [17], [28], [39]. Fig. 5 shows a detailed configuration of an eight-pole hybrid DR/HTS filter The filter consists of four DRs operating in image-type dual modes. The resonators are supported inside the filter housing using four blocks made of low-loss low-dielectric-constant ceramic materials. The HTS material is in the form of small wafers (0.5 in $\times$ 0.5 in at C-band), which are diced from a standard 2-in HTS thin film deposited on a 0.02-in-thick wafer of lanthanum aluminate. The HTS films are kept in contact with the DRs using springs and metallic plates bolted to the filter housing. A detailed description of this type of filter is given in [40].

The drawback of hybrid DR/HTS filters is the mechanical design complexity. They have, however, several advantages over their counterparts HTS thin-film planar filters. These advantages are as follows.

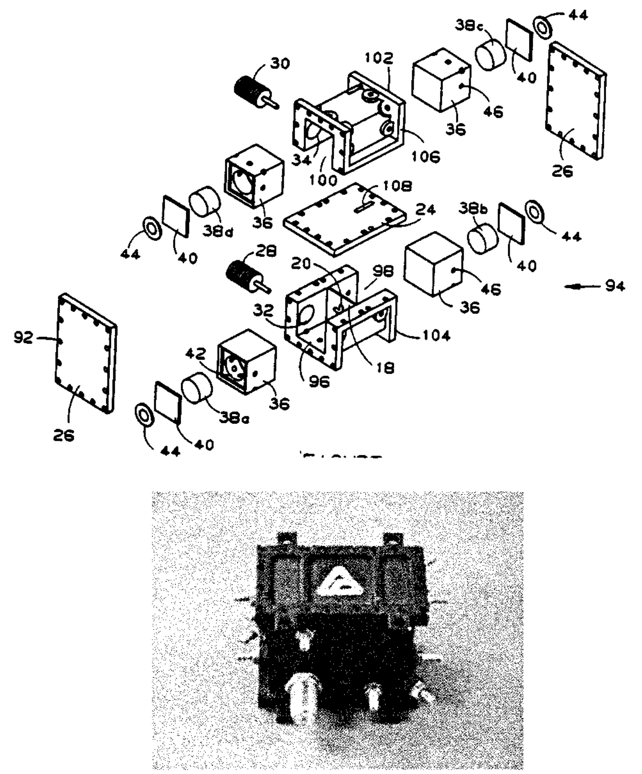

Fig. 5. Layout of the eight-pole hybrid DR/HTS filter. 38's are DRs, 40's are HTS wafers diced from a standard 2-in wafer, 36's are dielectric supports, 44's are spring washers, 26's, 102, and 104 are elements of the filter housing, and 28's are input/output probes.

1) No etching is required for the HTS material. Etching may reduce the power-handling capability of the HTS material and degrade its surface resistance. The design also eliminates the need to deposit gold contacts, which are required for thin-film filters. Also, there is no need to generate circuit and contact masks.
2) In patterned thin-film filters, a good portion of the HTS material is wasted due to etching process, while in hybrid DR/HTS filters, the wafer is diced into small pieces of "shorting plates." The wafer is used efficiently.
3) The filter has a good spurious performance. The image plate not only helps to reduce the filter size, but it also helps to eliminate spurious modes, making it possible to design filters of this type with a spurious free window of over 2-GHz width centered at a frequency of 4 GHz.

C. HTS Thick-Film Coated Filters

Melt-processed YBCO thick films were used to coat three-dimensional structures for microwave applications [41]. YBCO thick films typically have a current density of 2000 A/cm^2, and have a relatively small value of surface resistance of approximately 0.5 mΩ (5 GHz at 77 K). The feasibility of constructing a thick-film YBCO 5.66-GHz cavity resonator operating in TE_{011} modes with unloaded Q values of 715 000 at 77 K has been demonstrated in [42]. Measured results of cavities operating at 10 and 7.5 GHz have also been reported in [43]. However, the size of TE_{011} cavities is too bulky

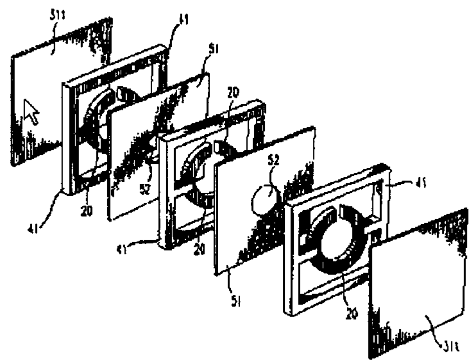

Fig. 6. Three-pole filter employing split-ring resonators coated with HTS thick films.

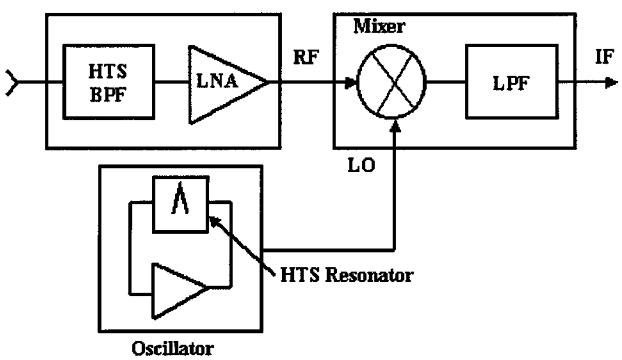

Fig. 7. Block diagram for an RF receiver.

to be used at frequencies below about 1–2 GHz. At lower frequencies, two resonator structures have been proposed for thick-film coating, i.e., coaxial resonators and split-ring resonators [44]. Thick-film coaxial resonators have found limited use because of the need to coat all of the surfaces in the cavity to achieve reasonably high-Q values. On the other hand, the split-ring resonator has been adopted by one of the wireless HTS base-station manufacturers. Fig. 6 illustrates a three-pole HTS filter employing split-ring resonators coated with HTS thick films. Coupling between resonators is achieved through the use of irises to provide the right coupling between resonators. Details on this type of filter can be found in [45].

Superconductive filters are also addressed in [46].

V. CRYOGENIC RECEIVERS

A layout of a typical receiver is shown in Fig. 7. In addition to signal amplification, the receiver typically provides frequency conversion to the transmit band. It consists of an input filter, a low-noise amplifier (LNA), an oscillator, and a down converter. The input filter limits the noise bandwidth and provides a high rejection of out-of-band signals. The insertion loss of this filter is a very critical parameter since it adds directly to the overall noise figure of the receiver. In most applications, these filters are typically built using high-Q filter structures to minimize the insertion loss. For example, a C-band input filter in satellite receivers is typically configured as a cascade of a waveguide low-pass filter and

TABLE II
MEASURED NOISE-FIGURE RESULTS OF Ka- AND C-BAND LNAs

Component	Measured Noise Figure at 300 K	Measured Noise Figure at 77 K
Ka-band LNA	3.1 dB	0.8 dB
C-band LNA	1.0 dB	0.25 dB

a waveguide bandpass filter. An HTS filter with a similar performance would have 1/16th the mass and 1/100th the volume of the conventional C-band waveguide input filter. It will also provide a 50% reduction in insertion loss.

The LNA benefits from cryogenic operation in two ways [47], [48]. The use of HTS matching structures results in decreased loss at the input of the LNA, which directly improves the attainable noise figure. Additionally, a fringe benefit of operation at 77 K is the reduction in the inherent noise of the active component. The improvement is more pronounced at high frequencies. Table II provides a summary of the typical measured noise-figure results of C- and Ka-band LNAs.

The oscillator could also benefit from using HTS technology by using a high-Q HTS resonator as the frequency-determining element. The benefit in this case would be phase noise reduction. However, cooling the remaining oscillator components will have a negligible impact on overall oscillator performance while adding a large heat load on the system. Therefore, the use of cryogenic technology has been limited in most applications to the input filters and the first few LNA stages.

VI. HTS DELAY LINES

Delay lines are useful devices in realizing transversal filters for analog signal-processing applications. Current technologies for delay lines include surface acoustic wave (SAW) devices and electromagnetic coaxial cables in the form of coils. However, the small acoustic wavelength and the minimum achievable linewidth limits the SAW delay devices to low-frequency applications. Electromagnetic coaxial transmission lines with much larger wavelengths can yield much higher frequency limits. On the other hand, coaxial delay lines are bulky and have high insertion losses. Often the use of amplifiers and equalizers is necessary to restore the original signal.

Superconducting delay lines [49]–[51] offer the highest bandwidth with the lowest loss in highly compact designs. Several HTS planar transmission lines such as striplines, microstrip, and coplanar lines could be used to realize delay lines. The high dielectric constant of lanthanum–aluminate substrates ($\varepsilon_r = 23.5$) allows a significant amount of delay to be placed on a single substrate, while the low conductor loss of the HTS material keeps insertion loss to a minimum. Fig. 8 illustrates a delay line realized using an HTS coplanar delay line.[5] A 100-ns HTS delay line of this type measures 90 mm $\times$ 96 mm $\times$ 12 mm. A 100-ns delay line realized using RG-141 cables would have a length of 70 ft. Even with a cryocooler, the size and weight reductions offered by the HTS technology are very attractive.

[5]DuPont Superconductivity, Wilmington, DE.

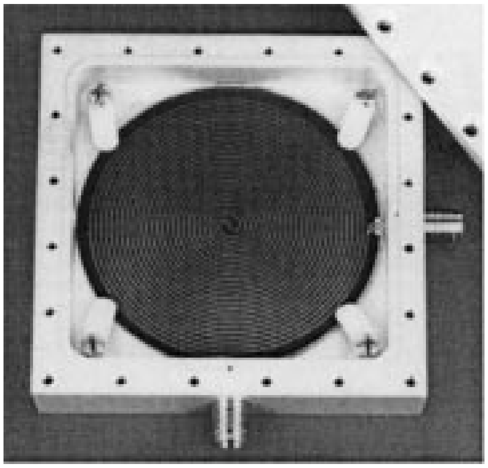

Fig. 8. Layout of an HTS delay line.

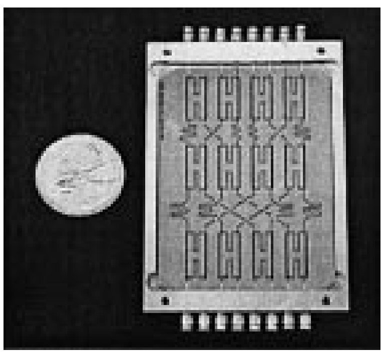

Fig. 9. 8 × 8 HTS Butler matrix.

VII. Antenna and Beam-Forming Networks

HTSs offer new opportunities for the designers of antenna systems. Examples include antenna matching elements, feed networks, microstrip antennas, and superdirective arrays [52]–[54]. In particular, beam-forming networks can benefit from HTS technology in both areas of insertion loss reduction and miniaturization. The current designs for beam-forming networks use either multilayer stripline technology or coaxial technology. The stripline designs are compact in size, but exhibit very high insertion loss. The coaxial designs, on the other hand, exhibit low loss, but are known to be very heavy and bulky.

Fig. 9 illustrates a layout of an HTS 8 × 8 Butler matrix designed to operate at L-band [54]. The matrix consists of folded thin-film 90° hybrids and delay lines. The size of the overall matrix is 75 mm × 50 mm × 12 mm. The HTS Butler matrix is two orders of magnitude smaller than its coaxial counterpart.

VIII. Wireless Applications

Mobile communication systems require improved sensitivity and selectivity to support the constant growth in services, increased coverage, and larger numbers of subscribers. In the last few years, several companies have taken advantage of technical innovations in cryoelectronics to address these improvements. Cryoelectronic solutions have matured to the point where numerous field trials under the auspices of both RF equipment manufacturers and PCS carriers have been proven to be successful [55]–[58].

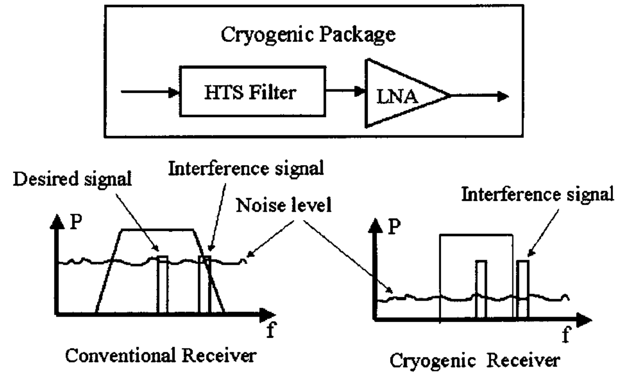

Fig. 10. Cryogenic package consisting of an HTS filter and LNA.

The performance of wireless base-stations can be considerably enhanced by incorporating cryogenic LNAs with HTS filters. The HTS technology presents a viable solution of realizing small-size high-order filters with low insertion loss. The overall size of multiple HTS transceiver chains, including the associated cryocooler, is considerably less than an equivalent conventional transceiver.

The capacity and coverage of a base-station receiver are determined primarily by the receiver selectivity and sensitivity on the up-link and, in part, by the base-station transmitter power of the downlink. The selectivity can be significantly increased with the use of high-order filters, as shown in Fig. 10. However, high-order filters, built using conventional technology, would exhibit a very high passband insertion loss, resulting in a reduced signal-to-noise ratio and, hence, degrading sensitivity performance of the receiver.

A significant improvement in receiver sensitivity can be achieved by designing the receiver to operate in a cryogenic environment. This virtually eliminates thermal noise from the LNA and potentially improves the filter loss performance. Although conventional DR filters can be cooled with some improvement in performance, integrated receivers of this type are too large for tower-top mounting.

The low resistance of the HTS materials makes it possible to use the planar thin-film technology to provide HTS filters that are two orders of magnitude smaller in size than conventional DR filters. This significant reduction in physical size makes valuable space available for other required electronic components, enabling service providers to enhance the utilization of existing base-stations instead of developing additional base-stations. In addition, miniaturization can decrease deployment costs for new base-stations, as less real estate is required to support the base-station. Fig. 11 illustrates a comparison between a conventional transceiver and an HTS transceiver [58].

IX. Space Applications

The mass, volume, and power consumption of payload electronic equipment are significant contributors to the overall cost of space systems. HTS technology offers the potential of large reduction in mass and volume of electronic equipment, leading

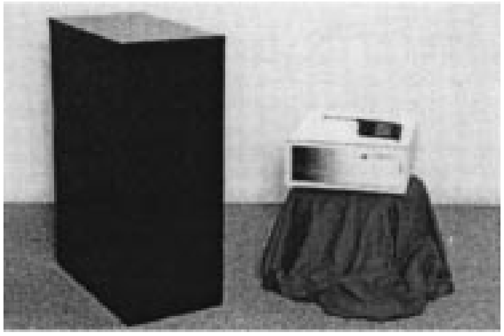

Fig. 11. Comparison between a conventional DR transceiver (left-hand side) and an HTS transceiver (right-hand side).

TABLE III
POTENTIAL IMPACT OF HTS TECHNOLOGY ON SATELLITE SYSTEMS

1. System and Component Mass Reduction
-Launch cost reduction
-Longer on-station time
-Additional payload capacity
2. Improvement in Noise Figure and Receiver G/T
-Effective increase in ground station EIRP
-Reduction in antenna size
-Possible cost impact to mobile services
-Improved link margin against rain or fading
3. Reduction in subsystem assembly and integration
-Potential cost reduction
-Potential improvement in delivery schedule
4. Prime Power Reduction
-Mass reduction
-Additional Capacity
5. Smaller satellite bus architectures due to miniaturization of electronic equipment

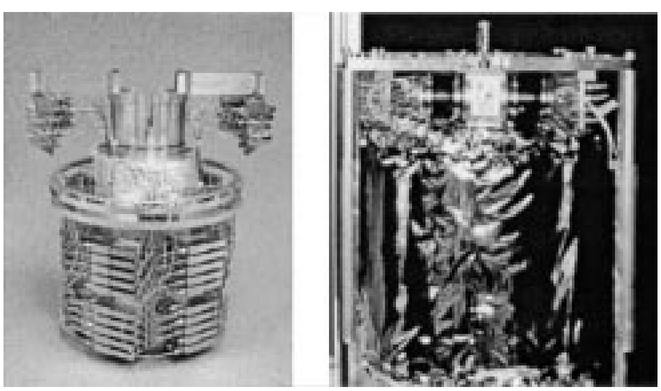

Fig. 12. 60-channel HTS multiplexer integrated with cryocoolers.

to significant cost reduction of satellite systems [35], [59], [60]. Today's space segment represents a market of many billion of dollars for commercial and military applications and is growing. HTS technology has the potential of accelerating the development and implementation of new advanced satellite systems. It also represents the potential of performance enhancements of strategic defense communications systems. An overall summary of the potential impact of HTS technology on satellite systems is given in Table III.

Mass reductions have a dramatic impact on the economics of a satellite program because launch costs are related to satellite weight. Similarly, mass reductions can be exploited to increase the capacity (by adding payload electronics) or extending operational life (by increasing station keeping fuel). As a result, market factors have constantly been pushing hardware suppliers to reduce mass and size of their products.

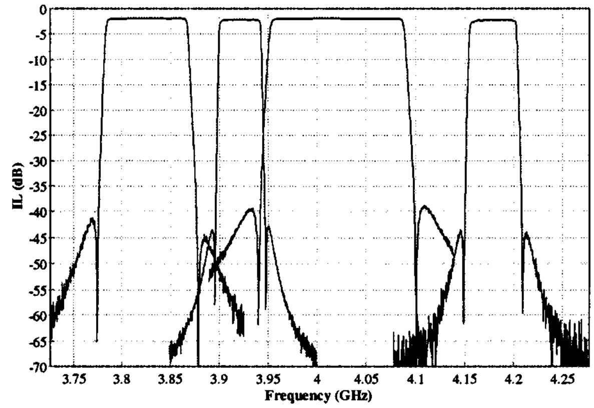

Fig. 13. Experimental results of four channels of the HTS 60-channel C-band input multiplexer.

TABLE IV
COMPARISON BETWEEN HTS TECHNOLOGY AND DR TECHNOLOGY FOR THE INTELSAT 8 C-BAND INPUT MULTIPLEXER

Parameter	Mass	Size
Conventional Dielectric Resonator Technology Including Mounting Hardware	25 kg	50×10^{-3} m^3
HTS technology including packaging, two cryo-coolers and two electronic-controllers.	12.2 kg	24×10^{-3} m^3
Percentage Saving	> 50 %	> 50 %

The current technology for satellite input multiplexers is the DR technology. A 60-channel HTS multiplexer was built [35] to duplicate the requirements of the Intelsat 8 C-band DR multiplexer. The channel filters are ten-pole self-equalized planar HTS thin-film filters of the type shown in Fig. 3.

Fig. 12 illustrates the overall 60-channel HTS multiplexer, while Fig. 13 shows the experimental results of four-channel HTS filters having a bandwidth of 34, 41, 72, and 112 MHz, which meet the bandwidth requirements of the Intelsat 8 program. Table IV summarizes the overall mass saving and size reduction. It can be seen that over 50% reduction in mass and 50% reduction in size can be achieved with the use of HTS technology [35].

There have also been efforts dedicated to the development of high-power HTS output multiplexers [39], [60]. Fig. 14 illustrates the layouts of a four-channel superconductive C-band output multiplexer and a similar conventional waveguide output multiplexer. For the conventional C-band multiplexer, both the channel filters and manifold are built using the waveguide technology. For the superconductive multiplexer, the channel filters are hybrid DR/HTS filters, while the manifold is realized using coaxial technology. The superconductive multiplexer occupies less than 5% of the volume of the waveguide multiplexer (without the cryocooler).

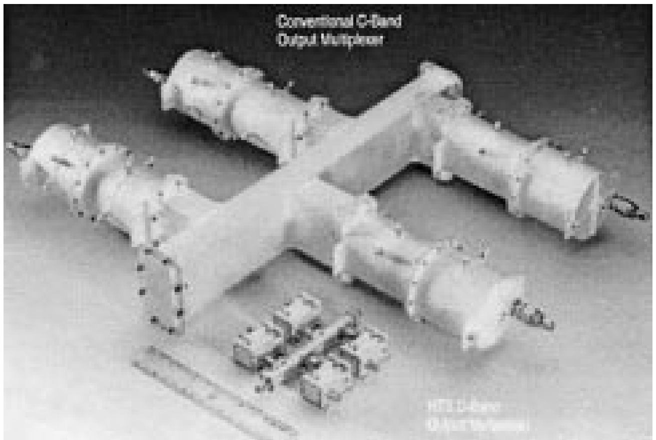

Fig. 14. Comparison between a C-band four-channel HTS output multiplexer and its waveguide counterpart.

The potential advantages of using HTS technology in the design of output multiplexers are mass and volume reduction, as well as insertion-loss improvement. The insertion-loss improvement can translate into improvement in satellite EIRP or reduction in the dc power required for the power amplifiers. However, the mass penalty of the currently available cryocooler and associated electronic controller may overshadow any advantages gained with the use of HTS technology for high-power output multiplexer applications [39].

X. Cryocooler Technology and Cryopackaging

Several cryocooler techniques exist that could meet the temperature needs for microwave HTS devices and subsystems. These techniques can be divided into two main categories, i.e., open and closed cycles [61]. The open-cycle techniques include cooling with a stored cryogen such as liquid nitrogen or through Joule–Thomson gas expansion. Open-cycle coolers are bulky and dissipate materials, requiring frequent fill up of the cryogen or compressed gas. Therefore, they are ideal for laboratory environments or in applications where regular equipment maintenance is possible.

Closed-cycle coolers are self-contained refrigerators that only consume electrical power, requiring no maintenance over the designed lifetime. Closed-cycle cryocoolers have been primarily developed for infrared devices and military applications. The main design considerations for a closed-cycle cryocooler are dc power consumption, size, and reliability. In particular, the reliability of the cryocooler remains the primary barrier to the widespread commercial acceptance of superconducting devices.

In addition to the cryocooler, it is also essential to provide a cryopackage with the means to mechanically and thermally attach the HTS microwave device to the cold head of the cryocooler within an evacuated enclosure, while providing electrical and RF cabling through the enclosure. One major challenge is to ensure low loss in the electrical connections without allowing too much heat to travel from the outside room-temperature environment to the HTS component. It is difficult to find commercially available RF cables that can reasonably meet the above two conditions. For example, having a cable with low-conduction heat load requires the use of a small-diameter cable. On the other hand, small-diameter cables typically have a high RF insertion loss. The choice of the RF and electrical connections to the package has a major impact on the size and cooling power of the cryocooler. Another major design issue is to guarantee that the enclosure maintains its vacuum over the operational lifetime of the system. Cryopackging is typically one of the main issues in the design of microwave HTS subsystems.

XI. Conclusions

HTS technology offers the potential of large reduction in mass and volume of microwave equipment. It could also provide performance discrimination not attainable with other technologies. The technology has grown very fast and has merged with commercial and defense applications. This paper has presented a summary of the main HTS microwave applications. Newcomers to the field are strongly urged to continue reading about the subject and to understand more about the potential, challenges, and limitations of this revolutionary technology.

Acknowledgment

The author would like to thank Dr. M. Nisenoff, M. Nisenoff Associates, Kensington, MD, for reviewing this paper's manuscript and for his constructive and helpful comments.

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Raafat R. Mansour (S'84–M'86–SM'90–F'01) was born in Cairo, Egypt, on March 31, 1955. He received the B.Sc. (with honors) and M.Sc. degrees from Ain Shams University, Cairo, Egypt, in 1977 and 1981, respectively, and the Ph.D. degree from the University of Waterloo, Waterloo, ON, Canada, in 1986, all in electrical engineering.

In 1981, he was a Research Fellow at the Laboratoire d'Electromagnetisme, Institut National Polytechnique, Grenoble, France. From 1983 to 1986, he was a Research and Teaching Assistant with the Department of Electrical Engineering, University of Waterloo. In 1986, he joined COM DEV Ltd. Cambridge, ON, Canada, where he held several technical and management positions in the Corporate Research and Development Department. In 1998, he became a Scientist. In January 2000, he joined the University of Waterloo, as a Professor in the Electrical and Computer Engineering Department. He currently holds a Research Chair at the University of Waterloo in RF technologies. He has authored or co-authored numerous publications in the area of electromagnetic modeling and high-temperature superconductivity. He holds several patents related to microwave filter design for satellite applications. His current research interests include superconductive technology, microelectromechanical system (MEMS) technology, and computer-aided design (CAD) of RF circuits for wireless and satellite applications.