Design Considerations of Superconductive Input Multiplexers for Satellite Applications

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Abstract—**This paper describes the evolution and development of low power superconductive filters and multiplexers for satellite applications under the HTSSE-II program. Experimental results and tradeoffs are presented for thin film and dielectric loaded HTS multiplexer configurations, leading to the development and implementation of a fully integrated four-channel C-band HTS input multiplexer. Measured data shows performance comparable to conventional technology and promise of large reduction in mass and volume of such equipment. The multiplexer is scheduled to fly as part of the HTSSE-II package on the ARGOS satellite in 1996.**

I. Introduction

OVER THE PAST two decades, remarkable improvements have been achieved in reducing the mass and volume of satellite communication payloads. A significant portion of these improvements has come from numerous innovations in the design of microwave filters and multiplexers [1]–[11]. The emergence of the high temperature superconductivity (HTS) has created another opportunity for more innovations in microwave components and subsystems for space applications.

The HTS technology has the potential of reducing the mass and volume of filters and multiplexers while providing a superior performance not attainable by any other technology [12]–[23]. We present in this paper a detailed comparison between conventional dielectric resonator technology and HTS technology for C-band input multiplexer applications. Owing to the large savings in mass and volume, the C-band input multiplexers are likely to be the first subassemblies in commercial satellite payloads that utilize the new HTS technology.

The paper presents experimental results for a four-channel C-band superconductive multiplexer developed under the Naval Research Laboratory (NRL) high temperature superconductivity space experiment (HTSSE-II) program. The multiplexer employs the circulator-coupled approach which is widely used for input multiplexer applications. The channel filters are eight-pole quasi-elliptic hybrid dielectric/HTS filters designed with 1% percentage bandwidth.

The major considerations for designing HTS input channel filters are discussed in detail. These include the impact of HTS material defects on the filter performance, limitations of existing CAD design tools, and thermal stability. The issue of group-delay equalization required for HTS input channel filters is also addressed. A comparison is given between the measured group delay of equalized and nonequalized hybrid dielectric DR/HTS eight-pole filters.

Experimental results are presented for other design options for input multiplexers: 1) A hybrid-coupled multiplexer employing single-mode HTS thin film filters; 2) a manifold-coupled multiplexer employing lumped element HTS thin film filters; and 3) a circulator-coupled multiplexer employing dual-mode HTS thin film filters. The HTS thin film filters discussed in this paper are designed using the state-of-the-art CAD design tools. The experimental results presented demonstrate the challenges involved in designing integrated HTS thin film multiplexer, with no tuning adjustment elements, for input multiplexer applications.

The paper also discusses the steps required to bridge the transition from R&D to commercialization of HTS technology for satellite applications.

II. Conventional Technology Versus HTS Technology for C-Band Input Multiplexers

In communication satellites, the available frequency spectrum is a primary resource. In order to utilize the allocated frequency spectrum as effectively as possible, guard bands between transponders should be minimized and hence sharp cutoff filters are desirable. Furthermore, the filters must have flat group delay and small gain slope to minimize the distortion and crosstalk. The types of filter designs that have been employed over the past three decades for C-band input multiplexer applications are: 1) high-order standard single-mode waveguide Chebyshev filters and equalizers (1971–1982); 2) dual-mode quasi-elliptic waveguide filters and equalizers (1978–1989); and 3) dual-mode self-equalized and externally equalized quasi-elliptic dielectric resonator filters (1983–present).

The first generation of satellite C-band input multiplexers were built with 24 input channel filters. In order to increase the

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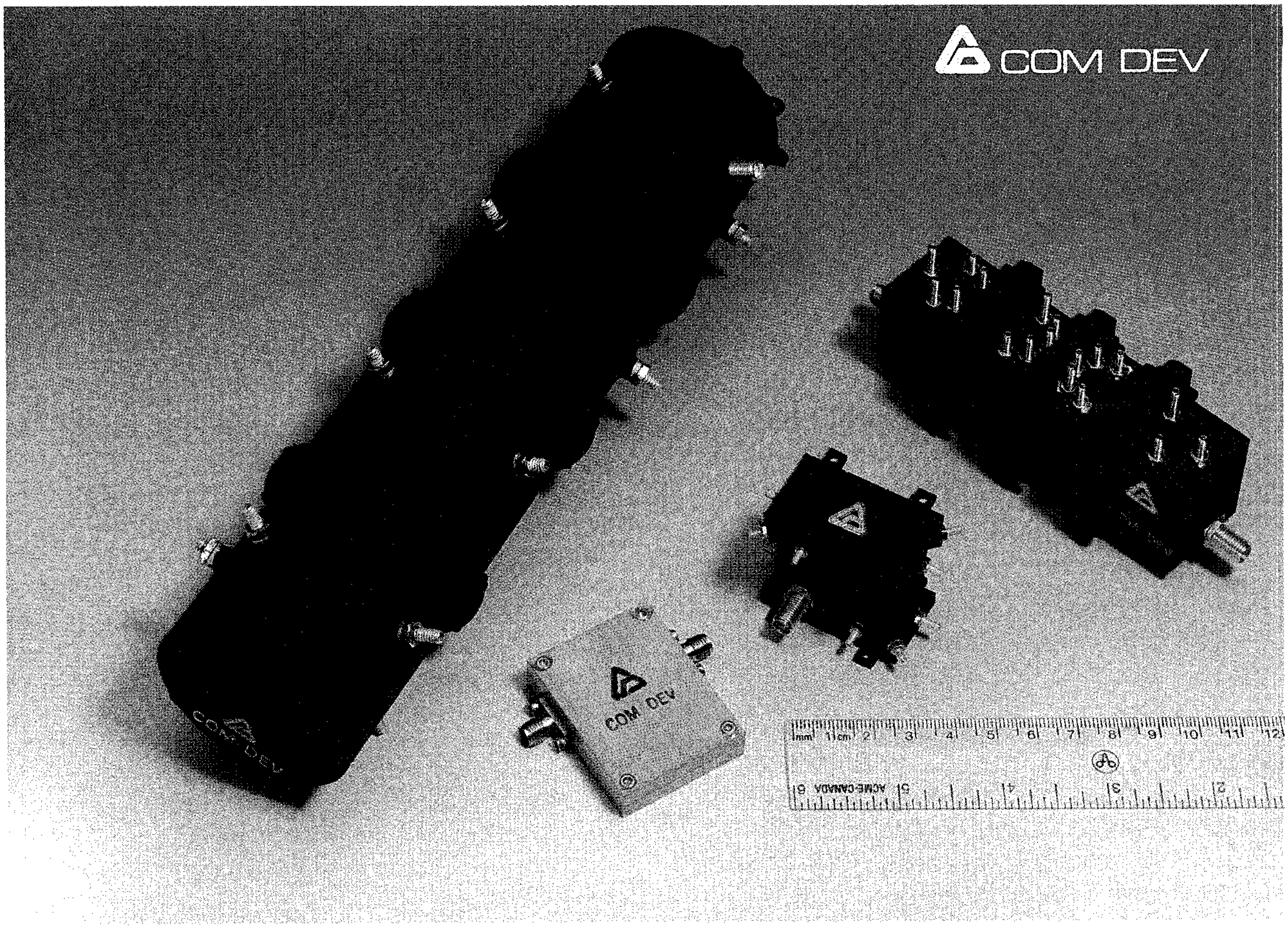


Fig. 1. A comparison between C-band input channel filters realized using waveguide technology, dielectric resonator technology, and superconductive technology.

communication capacity, there has been a push over the past decade to maximize frequency reuse and spot beams resulting in a greater number of transponders. As an example, the C-band input multiplexer of the INTELSAT 7 satellite (launched in 1993) has 44 input channel filters, while INTELSAT 8 satellite, which is currently under construction, has 60 input channel filters.

Owing to the large number of channel filters, the mass and volume of multiplexing equipment form a considerable portion of the overall satellite payload. Any reduction in this mass and volume can lead to greater communication capacity and/or increased lifetime, thus reducing the cost of a satellite channel. Fig. 1 illustrates a pictorial comparison between C-band input channel filters realized using waveguide technology, dielectric resonator technology and superconductor technology. 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.

A quantitative comparison between HTS technology and conventional dielectric resonator technology for C-band input multiplexers is presented in Table I. It can be seen that a considerable reduction in mass and volume is achieved with the use of the HTS technology. Since the input power level for C-band input multiplexer is typically less than -10 dBm, input multiplexers dissipate very little heat. In generating the data given in Table I, it is assumed that the mass of the cryo-cooler and associated electronics is 3 kg. Packaging of the filter equipment and its interface with the cryo-cooler may require an additional 2 to 3 kg.

The cryo-cooler would require some 20 watts of dc power for its operation. The equivalent battery and solar panel mass for this additional dc power would be 3 to 4 kg. However, this may be offset owing to the smaller spacecraft panel mass required to support the HTS multiplexer, which is less than two-tenth the volume of conventional dielectric resonator multiplexer.

In view of Table I, a payload mass saving of 17 kg can be potentially achieved with the use of HTS thin film technology. Such mass saving can add four to six months to the life of the spacecraft generating a substantial revenue. Alternatively, it may be possible to reduce the launch costs. Assuming a 1.2 kg of propellant mass saving for every 1 kg saved in payload mass, the overall GTO mass saving can be as high as 37.4 kg. This could provide a significant saving in launch cost.

Although, the potential saving in mass and volume, from inserting the HTS technology, is quite attractive, it should be mentioned that there is a number of hurdles still remain before this technology is likely to be deployed for commercial satellite systems. These include the availability of low-cost, reliable space-qualified cryo-cooler and the qualification of the

TABLE I
MASS AND VOLUME COMPARISON OF C-BAND INPUT MULTIPLEXER (INTELSAT VIII SATELLITE WITH 60 CHANNELS)

Parameter	Dielectric Resonator Technology	Hybrid DR/HTS Technology	HTS thin film Technology
Channel filters	26.2 kg	9 kg	4.2 kg
Cryo-cooler + Electronics	-	3 kg	3 kg
Cryogenic Package	-	3 Kg	2 kg
TOTAL MASS	26.2 kg	15 kg	9.2 kg
TOTAL VOLUME (including Cryo-cooler)	3120 in^3	790 in^3	480 in^3

HTS materials for space environment. An outline of the issues related to the commercialization of the HTS technology is given in Section IX.

III. DESIGN CONSIDERATIONS FOR HTS C-BAND INPUT MULTIPLEXERS

The design and fabrication of superconductive filters differ in many respects from the conventional filters. As with all emerging technologies, there are a number of problems to overcome before commercial products can be designed. The following sections outline the three major design issues for the realization of HTS input multiplexers.

A. Defects in HTS Films and Substrates

The performance of highly selective narrow band filters is quite susceptible to even minor defects in HTS films and substrates. It can be readily shown that a manufacturing defect or an inherent local defect that is in the range of 2 to 3 μm may cause about a 1 MHz deviation in the resonance frequency of a C-band HTS thin film resonator. The specifications of the present generation of satellite systems require that the center frequency of RF channels are held to within $\pm$300 kHz. As a consequence, a shift of 1 MHz in the filter center frequency would be unacceptable to the commercial satellite industry.

Similarly, small defects in the substrate in the form of nonuniformities, voids or twinning steps can also lead to substantial deviation in the resonance frequency of the filter elements. At the present time limited data is available on the variability of the dielectric constant from wafer to wafer or within a wafer. At C-band a difference in dielectric constant between 23.5 and 24 can cause a shift of 40 MHz which is more than the whole bandwidth of the channel filter.

The quality, uniformity and reproducibility of HTS films and substrate will certainly improve in the future. Nevertheless, in view of the stringent specifications of satellite input multiplexers, we believe that successful design of HTS channel filters, that meet all the specification requirements, necessitates the use of tuning adjustment elements. It should be also noted that tuning elements are still being used in the design of conventional C-band input multiplexers.

B. Design Tools for HTS Thin Film Filters

Several commercial packages have become recently available for simulation and design of microstrip circuits. These software packages are based on different electromagnetic (EM) numerical techniques. The choice of a numerical EM technique often involves trade offs between accuracy, computation speed, versatility and storage requirements. Because of these tradeoff parameters, most EM simulators are released with some inherent limitations. The fact that an EM simulator provides accurate results for one or two circuits does not guarantee that the same level of accuracy will be achieved for all circuits. Users may have to choose different EM simulators for different types of circuits [23].

Although, existing commercial software packages for microstrip circuits do not take the physics of superconductivity into account, some of these packages provide reasonably accurate results for HTS thin film filters [17], [21], and [22]. For HTS filters operating at low power, the impact of material defects and manufacturing tolerances on the filter performance far exceeds that caused by kinetic inductance effects.

One problem however with most of these EM packages is that they do not have built-in "optimization tools" which allow users to optimize the performance of a complete multiplexer. They are just "simulators." Although they may help users to accurately simulate circuits before building any hardware, the users must rely on other means to get the structural dimensions of the design. We have developed an algorithm to link optimization tools to commercial software packages. A description of this algorithm is given in [21]. This algorithm allows users to optimize HTS thin film circuits of any arbitrary topology.

The major problem with commercial EM simulators in the design of HTS thin film circuits is that they are very computation-intensive. The CPU time and memory space required to simulate a fully integrated HTS thin film multiplexer using present EM simulators far exceeds the capabilities of today's computer workstations.

Despite the fact that tuning elements would have to be eventually used to tune the channel filter performance to the required specifications, these CAD tools are considered a necessity. The role of the tuning elements should be restricted to "fine tuning." The task of designing HTS thin film filters without such advanced CAD tools would involve a great deal of trial and error efforts and more than likely would result in an inferior design.

C. Thermal Stability of the HTS Filters

HTS channel filters must be thermally stable to ensure performance repeatability as the temperature changes from cryogenic (testing) to room temperature (storage) and then back to cryogenic (operation). As mentioned earlier the center frequency of C-band input channel filters are typically maintained to within ±300 kHz. The extreme temperature changes, that the filter is exposed to, may cause a noticeable performance deviation.

The thermal stability problem is attributed to mechanical stresses in the tuning elements, the circuit carrier and the substrate. It is largely attributed to the mismatch between the thermal conductivity of the tuning elements and that of substrate or resonator. The problem could exist in both HTS thin film and hybrid DR/HTS filter designs, it is however more pronounced in the latter designs. This problem could be circumvented by careful choice of the materials of the circuit carrier and the tuning elements.

IV. Design Options for HTS C-Band Input Multiplexers

Conventional input multiplexers are built using the circulator-coupled approach shown in Fig. 2(a). For input multiplexers, the absolute insertion loss—as long as it is within few dBs—is not a constraint, This is due to the fact that noise figure is almost entirely governed by the front end receiver section. Any insertion loss after the receiver contributes little to the noise figure. As a consequence, the relatively lossy circulator-coupled approach is employed as it provides a maximum flexibility, both in terms of realization as well as in the layout of the input multiplexer. However, It should be mentioned that the minimum unloaded Q that must be achieved in channel filter is very important since it relates directly to the insertion loss variation and gain slope across the passband; two critical specifications for input multiplexers.

Fig. 2(b) and (c) illustrate two other multiplexing approaches that are amenable to the HTS thin film technology: the hybrid-coupled approach and the manifold-coupled approach. During the course of HTSSE-II program four different design options were evaluated by COM DEV for designing input multiplexers:

Option I: Hybrid-coupled multiplexer employing HTS thin film single-mode filters.

Option II: Manifold-coupled multiplexer employing HTS thin film lumped element filters.

Option III: Circulator-coupled multiplexer employing HTS thin film dual-mode filters.

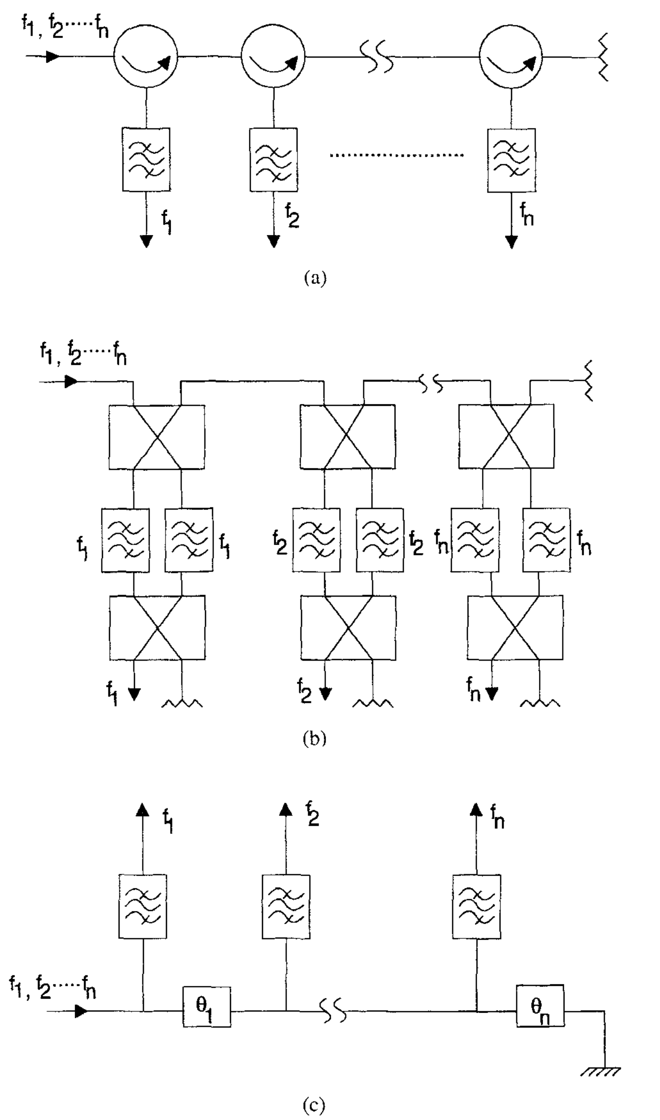


Fig. 2. Multiplexer layouts: (a) Circulator-coupled multiplexer; (b) hybrid-coupled multiplexer; and (c) manifold-coupled multiplexer.

Option IV: Circulator-coupled multiplexer employing hybrid DR/HTS thin film filters.

A summary of the advantages and disadvantages of these four approaches is given in Table II. Design options I and II were eliminated in the early stage of the program based on achievable performance of prototype hardware and limitations of existing HTS wafers and CAD tools. Design options III and IV were optimized for the development of a superconductive multiplexer that meets the interface requirements of the HTSEE-II package. Design option IV was eventually selected as the baseline design for the HTSSE-II flight package. The following sections present the results achieved and provide a description of the limitations and evolution of each design option.

V. Design Option I: Hybrid-Coupled Multiplexers Employing HTS Thin Film Single-Mode Filters

The layout of a hybrid-coupled multiplexer is given in Fig. 2(b). Each channel consists of two identical filters and

TABLE II
THE CRITICAL DESIGN ISSUES OF THE FOUR DESIGN OPTIONS

Parameter	Design Option I	Design Option II	Design Option III	Design Option IV
Sensitivity to defects in films and substrate	Medium	High	Medium	Low
Tunability	Difficult	Very difficult	Difficult	Easy
Temperature stability	Good	Good	Good	Fair
RF design complexity	High	Very High	High	Medium
Mechanical design complexity	Medium	Low	Medium	High

two identical hybrids. The main advantages of the hybrid-coupled approach, is that it is amenable to a modular concept allowing ease of integration of a large number of channels [17], [22]. Multiplexers employing this approach have relatively larger size since they require the use of two filters and two hybrids per channel. This approach is also not compatible with the sizes of commercially available HTS wafers to build high-order high-Q filters for input multiplexer applications.

To evaluate the limitations of this approach when it is applied to HTS thin film technology, a 2-channel multiplexer (diplexer) was built and tested. Fig. 3 illustrates the diplexer layout. The whole diplexer was constructed on a lanthanum aluminate wafer of size 3.5 cm × 3.5 cm. Channel 1 was realized using two filters and two hybrids. In order to fit the whole diplexer on one wafer, channel 2 was constructed using a single filter. The experimental results achieved are shown in Fig. 4 It can be seen that the diplexer performs its intended function of separating the composite input signals into two channels. It should be mentioned that the results given in Fig. 4 were obtained without the use of any tuning mechanisms.

One of the major considerations in the design of thin film hybrid-coupled multiplexer/diplexers is the phase deviation between the two filter paths which the two signals undergo before they add constructively at the channel output. Defects in the lanthanum aluminate wafer in the form of nonuniformities or twining may lead to substantial deviations in the performance of the two identical filters which in turn may degrade the overall performance of the multiplexer.

As large size HTS wafers become available in the future, it may be possible to use this approach for C-band input multiplexer applications. External equalization of thin film filters can be implemented as shown in Fig. 5. The equalizer consists of an isolator, a hybrid and two sets of resonators. With the use of a drop-in type isolator the channel filter and equalizer could be integrated on one large wafer.

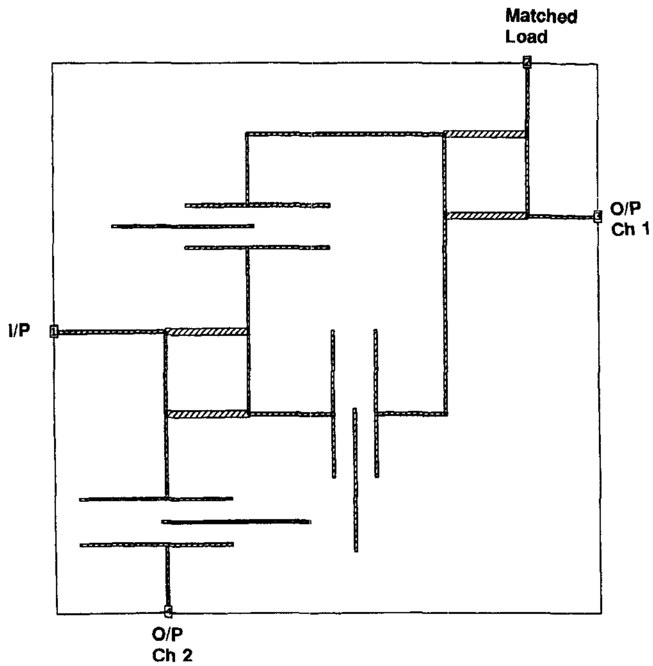


Fig. 3. Layout of a two channel hybrid-coupled multiplexer realized on a lanthanum aluminate wafer of size 1.4″ × 1.4″.

VI. DESIGN OPTION II: MANIFOLD-COUPLED MULTIPLEXERS EMPLOYING HTS THIN FILM LUMPED ELEMENT FILTERS

The manifold-coupled approach shown in Fig. 2(c) is viewed as the obvious choice as far as miniaturization and absolute insertion loss are concerned, However, manifold coupled multiplexers are not amenable to a flexible frequency plan. Since interaction between filters on the manifold must be taken into account, any changes in one of the channels will require a new multiplexer design. Moreover, as the number of channels increases, this approach becomes more difficult to implement due to design complexity and size limitations of commercially available HTS wafers.

The use of HTS lumped element (LE) filters rather than conventional distributed circuit-type filters will allow integration of large number of channels on the same wafer. Although, a great deal of work has been reported on HTS distributed filters, only few papers have been reported on HTS lumped element filters. Most of the LE filter topologies require the use of via-holes or air-bridges. The lack of proven processes for fabricating via-holes and air bridges on HTS films has limited the application of HTS LE filters.

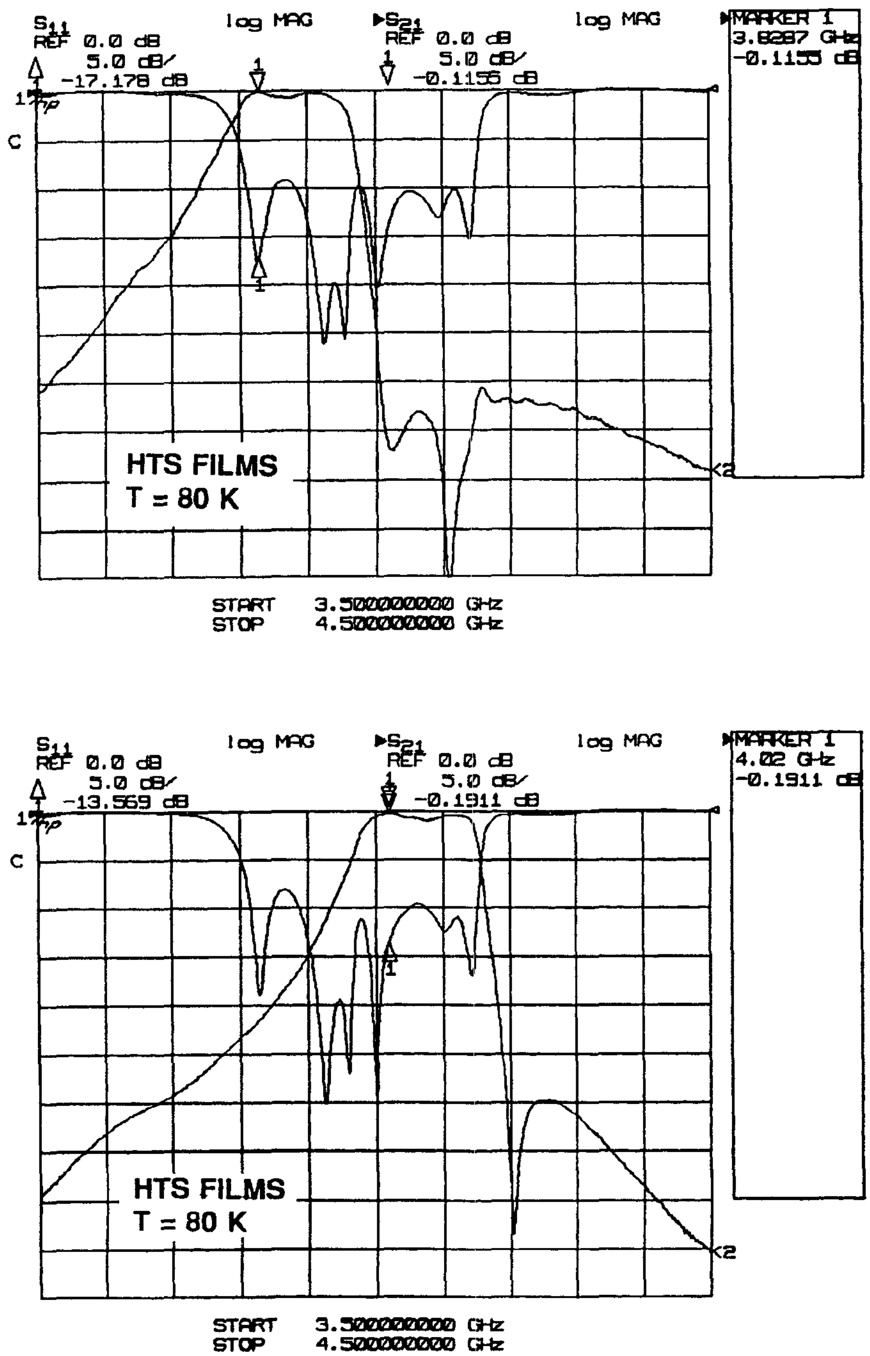


Fig. 4. The measured performance of the two channel multiplexer shown in Fig. 3.

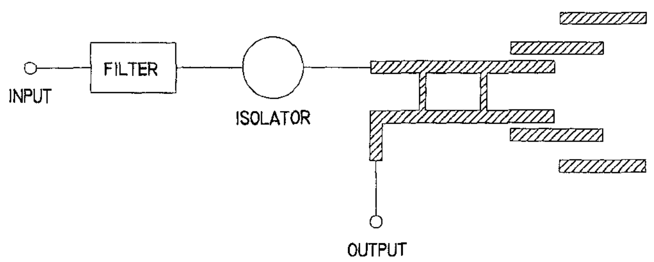


Fig. 5. An external equalizer circuit for HTS thin film filters.

Fig. 6 shows the layout of a six-pole LE filter with a topology that does not require the use of via-holes or air-bridges. The filter has 2% bandwidth and is built on lanthanum aluminate wafer of size 1.5 cm × 1.0 cm. The measurements of the gold film version taken at 300 K and 77 K are shown in Fig. 7(a) and (b). The gold film filter exhibits an insertion loss of 30 dB and 15 dB, respectively. The measured performance of the HTS film version built on a single-sided YBCO wafer is shown in Fig. 7(c). The HTS film version exhibits an insertion loss of only 0.5 dB.

Fig. 8 illustrates a 3-channel manifold-coupled multiplexer employing six-pole LE filters of the type illustrated in Fig. 6. The whole multiplexer was designed on a lanthanum aluminate wafer of size 3.75 cm × 3.25 cm. The manifold is constructed using microstrip T-junctions. Existing EM simulators that

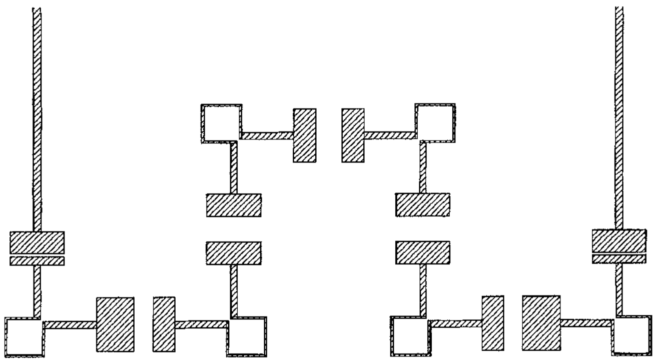


Fig. 6. Layout of an six-pole lumped element HTS thin film filter.

provide reasonably accurate results are very computational-intensive. The use of such EM simulators in the design and optimization of fully integrated manifold coupled multiplexer is prohibitively long. In designing the multiplexer shown in Fig. 8, the role of the EM simulator was limited to the analysis of the basic building blocks of the multiplexer: the microstrip T-junctions and the LE filter inductors and capacitors. A circuit-theory approach was then used to cascade the basic elements to construct the multiplexer. The interaction between the different resonator elements of the three filters due to surface wave was not taken into consideration in designing this multiplexer. Fig. 9 illustrates the computer optimized performance based on this semi-EM approach.

The multiplexer was built using gold films and single-sided YBCO films. A comparison between the experimental results achieved for the gold film and HTS film versions is given Fig. 10. The disagreement between the theoretical and experimental results, given in Figs. 9 and 10, is attributed to the semi-EM design approach used in designing this multiplexer and to the high sensitivity of the lumped element filters to materials defects.

With the use of an 3″ HTS wafer, it is possible to integrate a four-channel multiplexer employing eight-pole filters of the type shown in Fig. 6 on one wafer. However, in view of the currently available state-of-the-art HTS materials and CAD design tools, the task of successfully designing HTS integrated C-band manifold-coupled input multiplexers, with no tuning mechanisms, is quite formidable.

VII. Design Option III: Circulator-Coupled Multiplexers Employing HTS Thin Film Dual-Mode Filters

Conventional C-band circulators are typically designed to operate over a temperature range of −50 c to +100 c. For operation at 77 K the garnet resonant frequency will shift up or down depending on the circulator design concept whether it is "above resonance" or "below resonance." With the knowledge of the saturation magnetization at cryogenic temperatures, it is possible to redesign the circulator to operate at such extremely low temperatures.

A number of cryogenic circulators have been designed to operate over the temperature range 65 K to 77 K. These

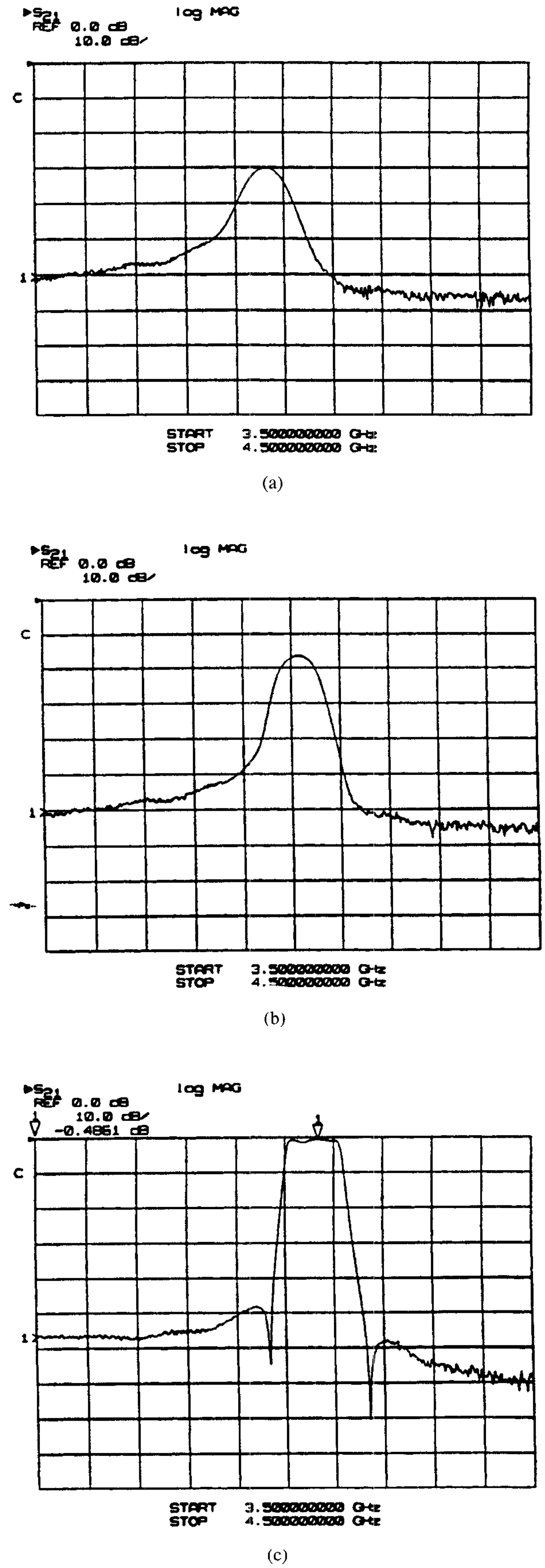


Fig. 7. The measured performance of the six-pole lumped element filter shown in Fig. 6. (a) Gold film at 300 K. (b) Gold film at 77 K. (c) Single-sided YBCO films at 77 K.

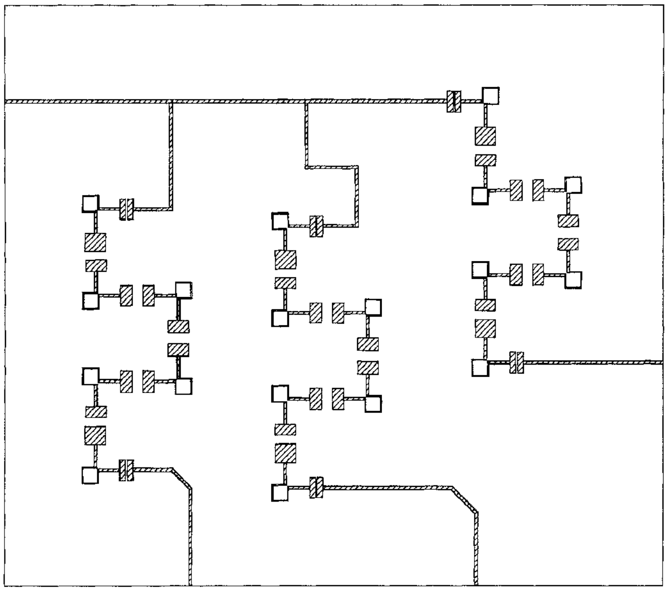


Fig. 8. The layout of a manifold-coupled multiplexer employing three six-pole lumped element filters.

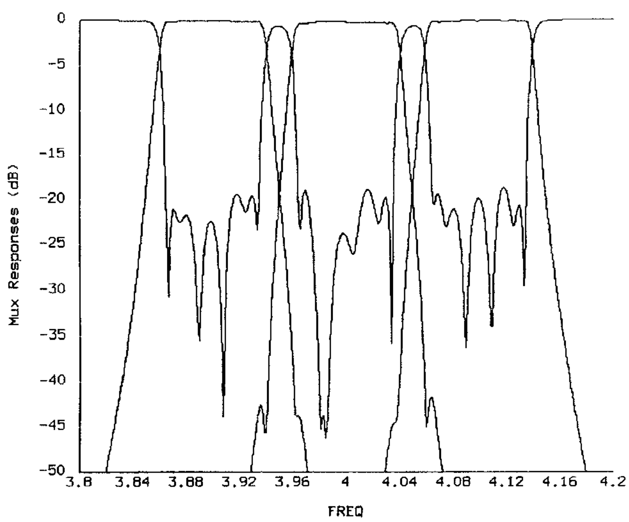
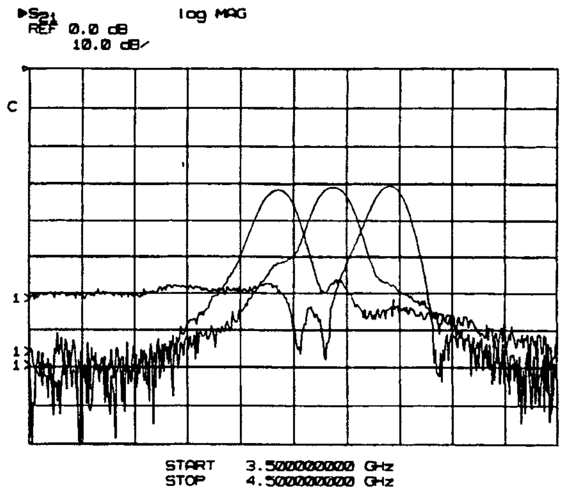
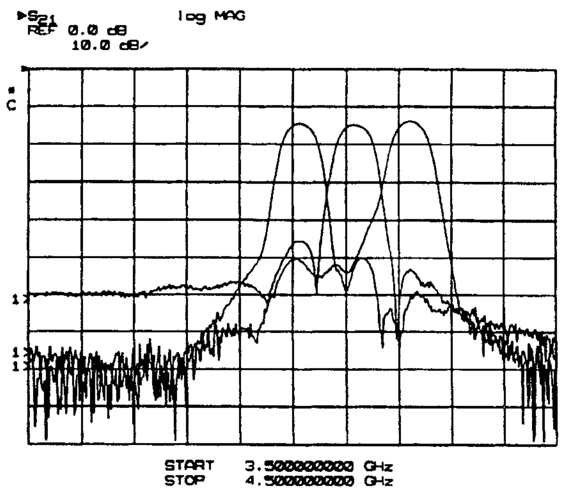


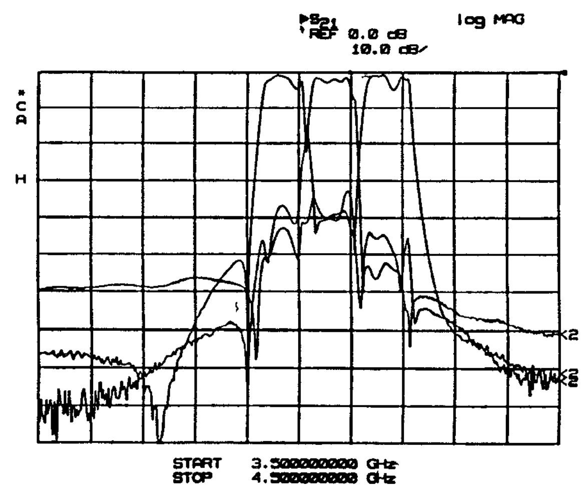
Fig. 9. The computer optimized performance of the multiplexer shown in Fig. 8 using a semi-EM design approach.



(a)



(b)



(c)

Fig. 10. The measured performance of the multiplexer shown in Fig. 8. a) gold films at 300 K. b) Gold films at 77 K. c) Single-sided TBCCO films at 77 K.

circulators are of conventional-type having no superconductor materials. Fig. 11 shows the measured RF performance of a C-band circulator at 77 K. The circulator exhibits an insertion loss of 0.21 dB, a return loss of 25 dB and an isolation of 25 dB over a bandwidth of 500 MHz. The RF performance given in Fig. 11 is comparable to that of conventional room temperature C-band circulators.

The idea of using dual-mode microstrip resonators, in the form of a circular patch or a square patch to build dual-mode filters has been known for many years [24]–[26]. With HTS films replacing gold films, microstrip patch resonators can be potentially employed to design dual-mode HTS filters [16],[21]. More recently, experimental results are presented for a 3-channel multiplexer employing 4-pole HTS filters of this type [21].

Fig. 12 illustrates two possible configurations for eight-pole dual mode filters having Chebyshev and quasi-elliptic

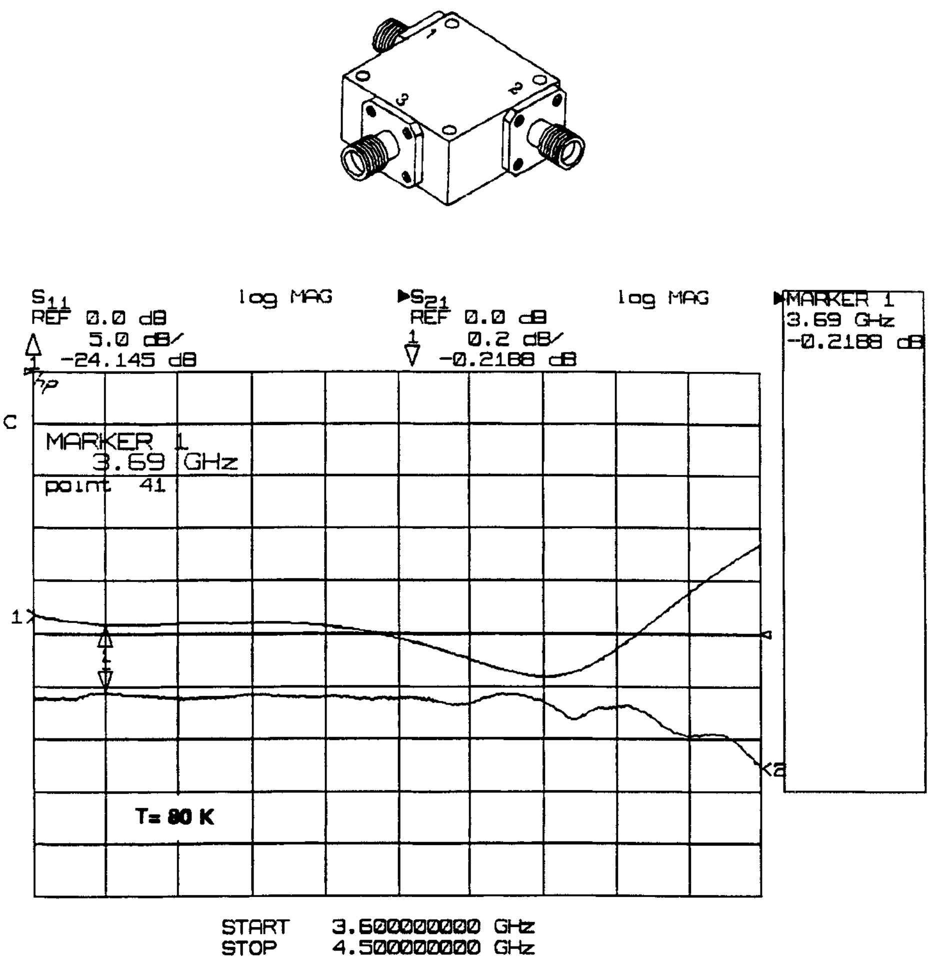


Fig. 11. The measured performance of a cryogenic C-band circulator at 77 K.

functions. The quasi-elliptic filter is chosen to have two pairs of transmission zeros. It can be seen that the use of dual-mode microstrip patch-resonators makes it easy to couple between nonadjacent (electrically) resonators which in turn allows the realization of elliptic function filters. Other advantages of dual-mode disk resonators over conventional single-mode resonators are higher Q and less sensitivity to manufacturing and material defects.

Fig. 13 shows the layout of a four-channel circulator coupled multiplexer employing four eight-pole dual-mode HTS thin film filters. The filters have a 1% bandwidth and are realized using single-sided thallium wafers. RF connection between the channel filters and the cryogenic circulators is provided via 0.085 stainless steel coaxial cables. The whole multiplexer is integrated on a plate of size 7.8 cm × 11.4 cm.

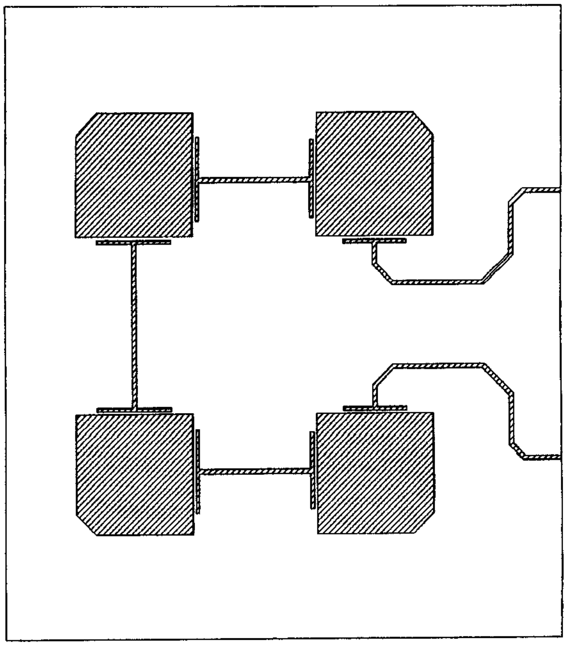
The CPU time and memory required to optimize the performance of the filters shown in Fig. 12, using commercial EM simulators, far exceeds the capability of today's computer workstations. The four filters were therefore designed using a semi-EM approach where coupling between nonadjacent patches was not taken into consideration. The measured performance of the multiplexer given in Fig. 13 is shown in Fig. 14. It should be noted that no tuning screws or any other tuning mechanisms were used to achieve the results shown in Fig. 14.

VIII. Design Option IV: Circulator-Coupled Multiplexer Employing Hybrid DR/HTS Filters

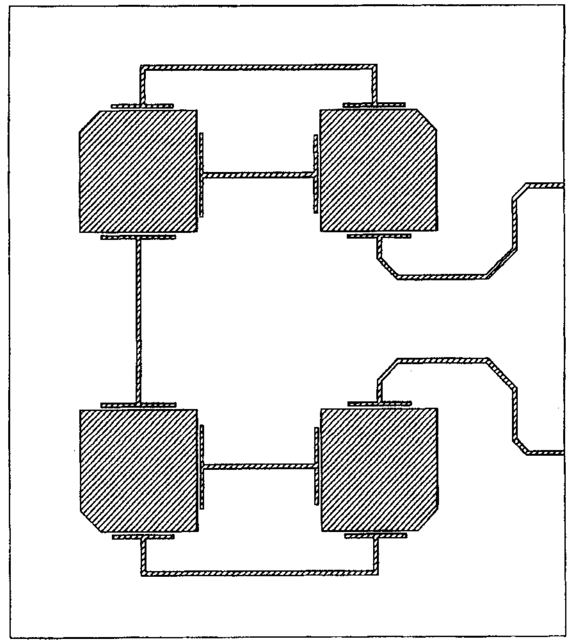
In Sections V, VI, and VII we outlined the challenges encountered in designing multiplexers employing HTS thin film filters. It became clear over the course of our development efforts that the HTS thin film technology (material and CAD design tools) is not advanced yet to allow the development of an integrated multiplexer that can meet the stringent requirements of satellite input multiplexers.

The main advantages of hybrid DR/HTS filters over HTS thin film filters described in Sections V–VII are ease of tunability and less sensitivity to material defects. The major drawbacks are mechanical design complexity and cost of production. Additionally, hybrid DR/HTS filters are slightly larger in mass and volume than purely HTS thin film filters.

For the present C-band satellite systems, dielectric resonator filters are emerging as the baseline design for input multiplexing networks. A conventional dielectric resonator filter consists of a number of dielectric loaded cavities operating either in



(a)



(b)

Fig. 12. Two possible configurations for eight-pole dual-mode filters. (a) Chebyshev filter. (b) Quasi-elliptic filter.

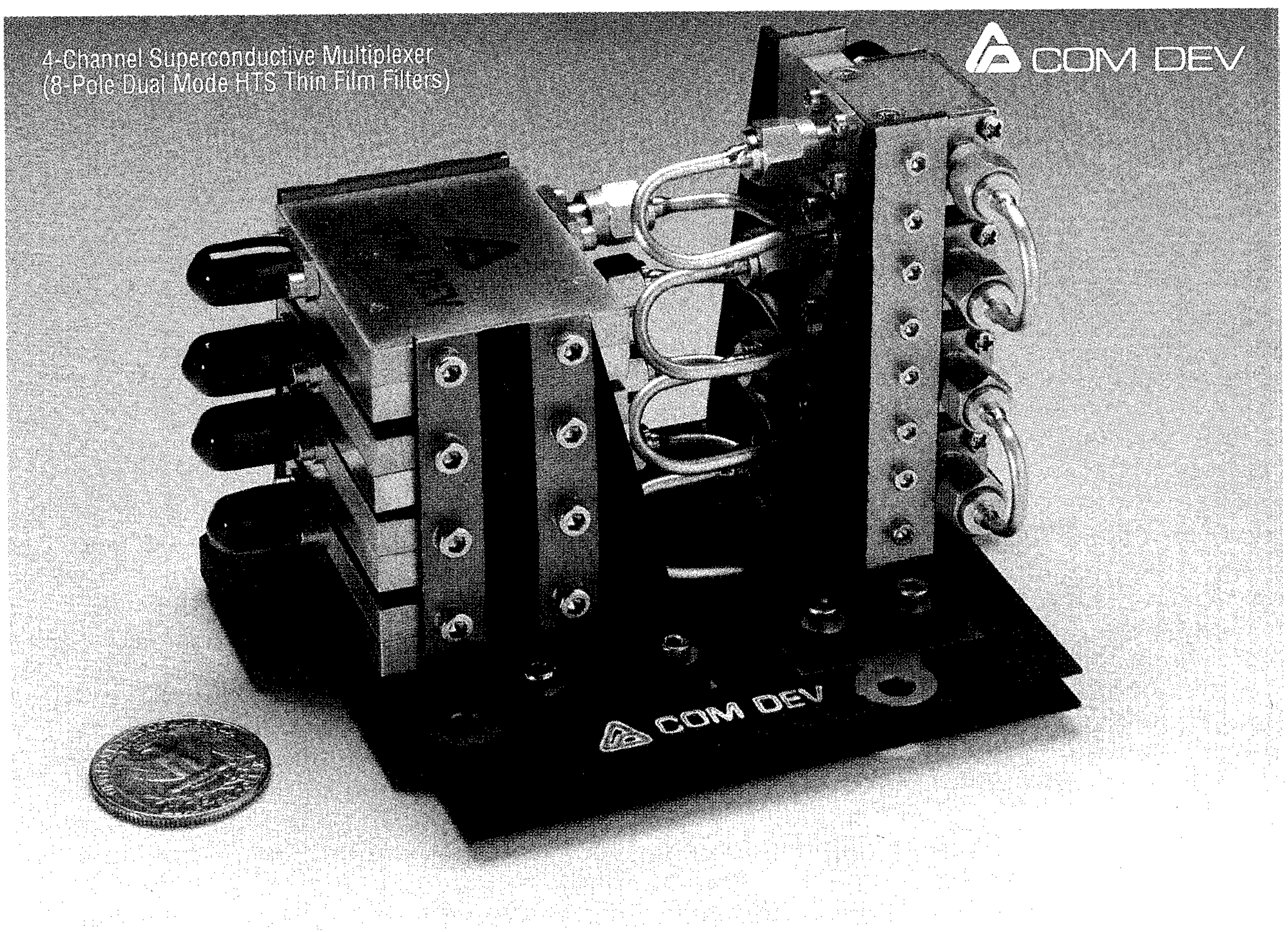


Fig. 13. The layout of a circulator-coupled multiplexer employing eight-pole dual-mode HTS thin film filters.

dual-modes or single-modes. The typical cavity size at C-band is 1.0″× 1.0″ × 1.0″ and the typical achievable Q is 10 000.

The size and mass of the dielectric resonator filters can be reduced by using the concept of image-type resonators where

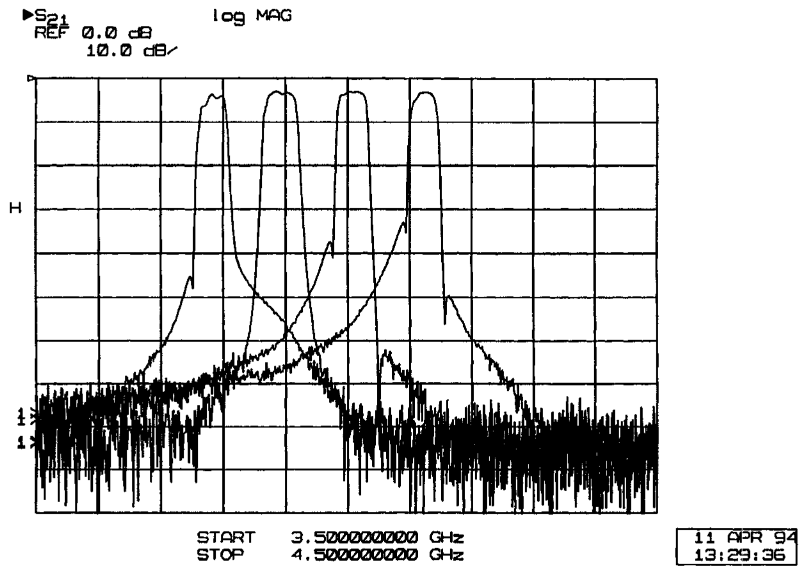


Fig. 14. The measured performance of the superconductive multiplexer shown in Fig. 13.

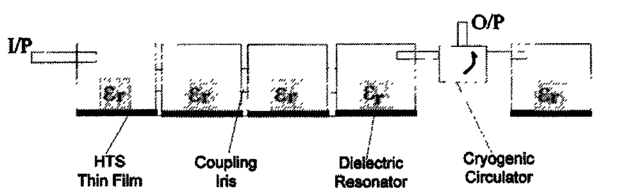


Fig. 15. The layout of an eight-pole externally equalized hybrid DR/HTS filter.

a smaller size resonator is placed in contact with a conducting plate. A normal conducting plate will however significantly degrade the resonator Q. By replacing the conducting plate with a plate that made out of HTS thin film materials, considerably high Q values can be achieved [18].

Fig. 15 illustrates the configuration for an eight-pole externally-equalized hybrid DR/HTS filter. The filter structure comprises of square cavities of size 0.5″ × 0.5″ × 0.5″ separated by irises. The dielectric resonators can be held in contact with the shorting plate using plastic screws inserted from the cavity top wall or by any other means. The cavities and the irises are bolted together by screws to form the filter. The image-plate is made out of HTS thin films printed on any dielectric substrate. The dielectric constant of this substrate material has no effect on the filter performance.

Fig. 16 depicts the measured performance of an eight-pole hybrid dielectric/HTS filter having a percentage bandwidth of 1%. The filter function is quasi-elliptic with two pairs of transmission zeros. The HTS filter exhibits a performance similar to what can be achieved with the current dielectric resonator technology. This HTS filter however has 1/8 the size of conventional filters.

The filter is externally equalized using a cryogenic circulator and an all-pass single cavity containing a hybrid dielectric/HTS dual-mode resonator. The cryogenic circulator is of the type described in Section VII. A comparison between the measured group-delay performance of nonequalized and equalized eight-pole hybrid DR/HTS filters is given in Fig. 17. The nonequalized filter exhibits a group-delay variation of 45 ns over 90% of the filter passband, while the equalized filter exhibits only a variation of only 6 ns over the same frequency band.

Fig. 18 illustrates the layout of a four-channel C-band circulator-coupled multiplexer employing eight-pole hybrid dielectric/HTS filters having 1% bandwidth. The overall size of the superconductive multiplexer including the mounting plate is 7.8 cm × 11.4 cm × 8.1 cm. The measured overall performance of the four-channel superconductive multiplexer at 77 K is given in Fig. 19. Channel #1 exhibits a minimum insertion loss of 0.26 dB. This overall loss is the sum of the losses encountered in the cryogenic circulator, the 0.085 stainless steel cable and the superconductive filter. Channels 2, 3, and 4 exhibit a relatively higher insertion loss due to insertion loss incurred at each trip through the channel dropping circulators.

A comparison between the superconductive multiplexer shown in Fig. 18 and a conventional four-channel C-band input multiplexer built by COM DEV for a recent satellite program is depicted in Fig. 20. The volume of the HTS multiplexer is less than two tenth the volume of the conventional dielectric resonator multiplexer. The superconductive multiplexer model shown in Fig. 18 was vibration tested per the requirements of the HTSSE-II program. The results achieved demonstrate performance repeatability and confirm the structural integrity of this multiplexer for space applications [18].

IX. Concluding Remarks

The C-band four-channel input multiplexer presented in this paper demonstrates the reduction in mass and volume achieved with the use of HTS technology. Such reduction in mass and size can directly translate into saving in launch cost or into more communication capacity. This multiplexer employs

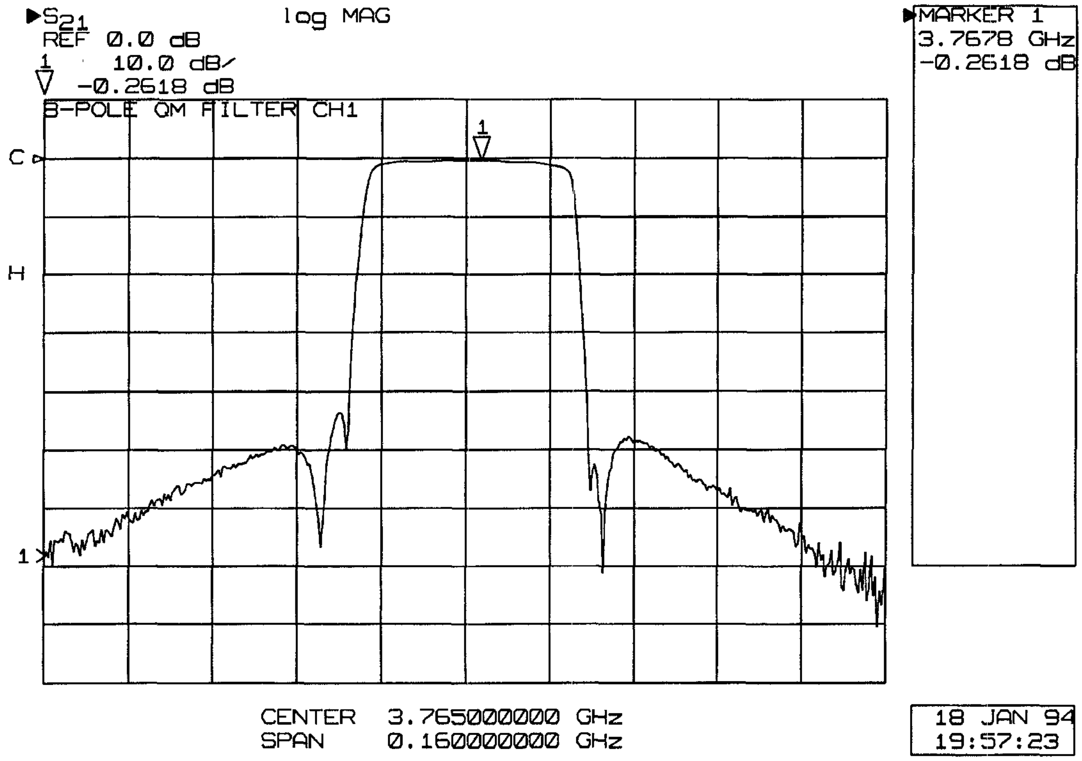
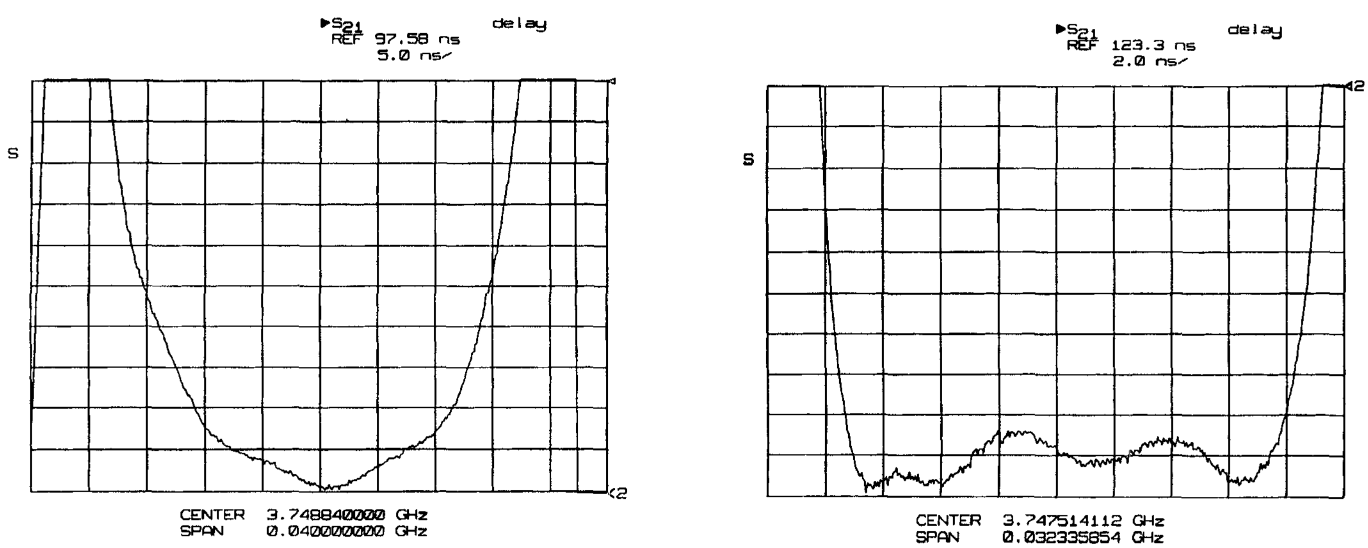


Fig. 16 The measured performance of a hybrid DR/HTS filter having a 1% percentage bandwidth.



(a) (b)

Fig. 17. A comparison between the group delay performance of equalized and nonequalized filters. (a) Nonequalized. (b) Equalized.

hybrid DR/HTS filters which can be easily tuned to the typical requirements of input multiplexers. However, it can be seen from the comparison given in Section II that a larger saving in mass and volume can be achieved with the use of integrated HTS thin film filters rather than hybrid DR/HTS filters. Owing to simplicity in fabrication and assembly, HTS thin film filters also have the potential to be more cost effective.

Although the progress achieved over the past four years in designing HTS thin film filters is remarkable, there are still many hurdles to overcome before HTS thin film technology can be used in subsystems with stringent requirements such as satellite input multiplexers. The major issues are: limitations of existing CAD tools, and lack of efficient tuning mechanisms for HTS thin film circuits.

The primary limitations of existing CAD tools are attributed to the fact that present EM simulators are considered very computation-intensive to run on today's computer workstations. The most reliable approach for designing HTS thin

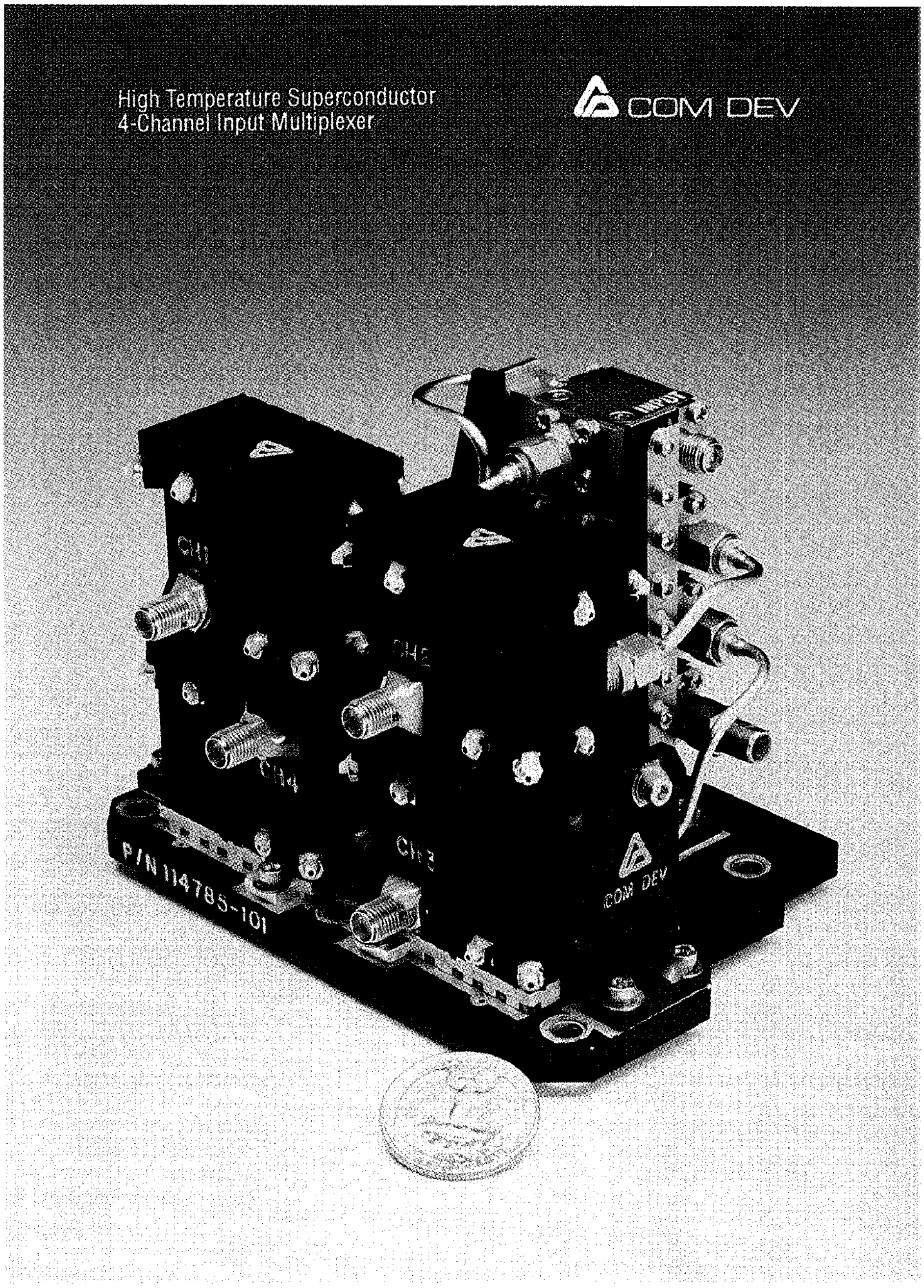


Fig. 18. A layout of a four-channel C-band superconductive input multiplexer employing eight-pole hybrid DR/HTS filters.

film circuits is to use a CAD algorithm consisting from an EM simulator and an optimization package [21]. For some HTS thin film circuits, the CPU time required to complete the optimization process could be extremely large. For example, optimizing the performance of the thin film filter shown in Fig. 12, using existing commercial EM simulators, may require more than 250 M bytes of memory and can take a CPU time of more than two months on an HP735 workstation. Designing the three-channel lumped element manifold-coupled multiplexer shown in Fig. 8 using the same approach can take more than four months for one design iteration. However, it should be mentioned that in view of the rate at which the computer technology is advancing, the CAD design tools may not be an issue in the near future.

The HTS thin film technology in not easily amenable to conventional tuning mechanisms. Although fine-tuning of the HTS thin film filters may not be required in many applications, designing an equalized 1% bandwidth eight-pole quasi-elliptic HTS thin film filter with a center frequency that is maintained to within 300 kHz necessitates the use of tuning elements. Both the waveguide and dielectric resonator technologies have been known for more than two decades. Nevertheless, tuning screws are still being used in designing filters for input multiplexer applications. The tuning issue needs therefore to be addressed before purely HTS thin film filters can be used for satellite applications.

The HTS technology offers the potential of large reduction in mass and volume of electronic equipment, leading to

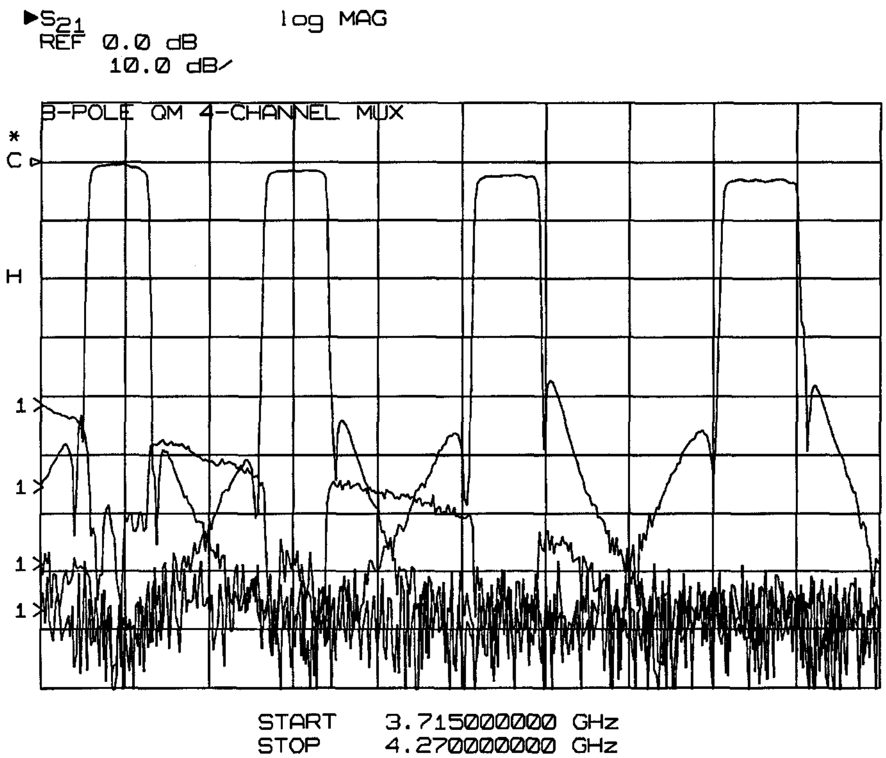


Fig. 19. The measured performance of the superconductive multiplexer shown in Fig. 18 at 77 K.

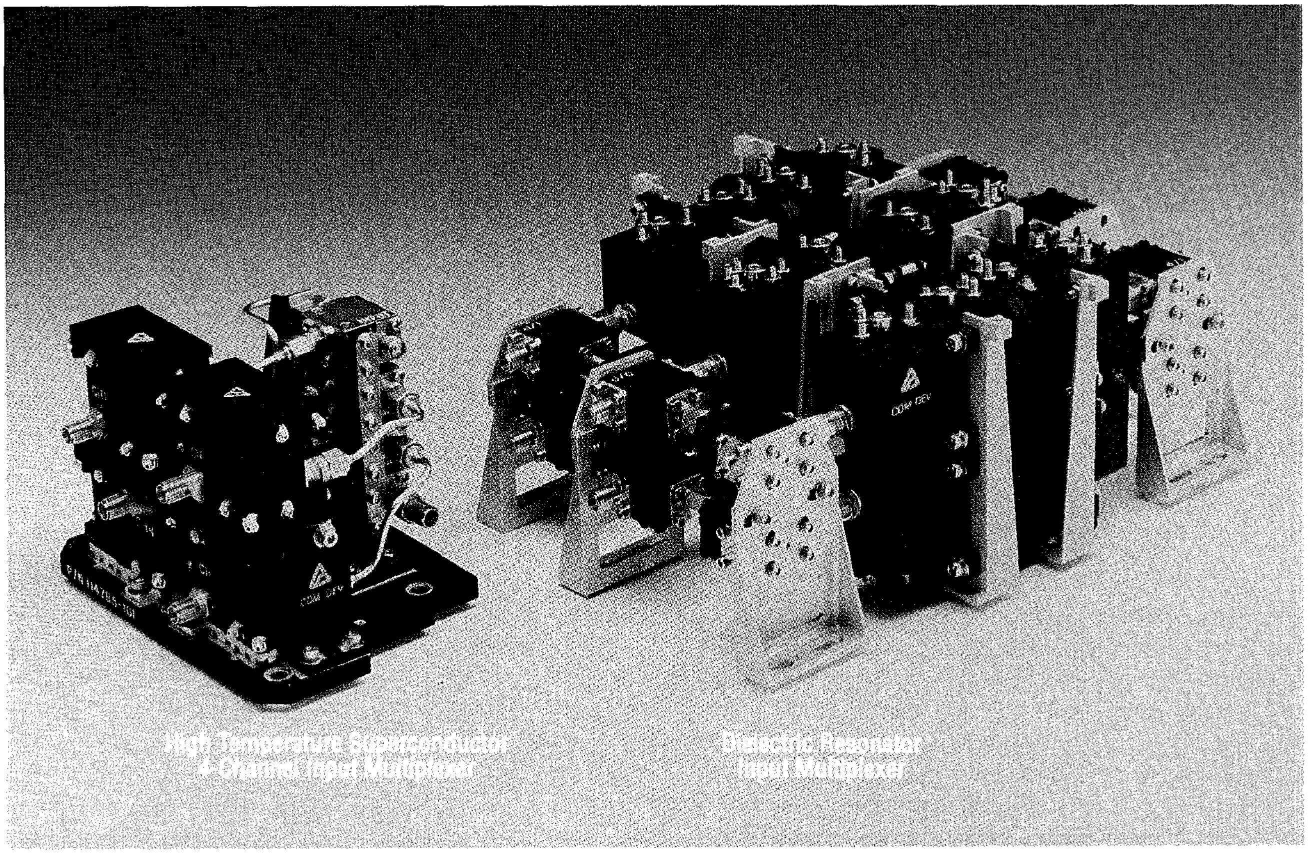


Fig. 20. A comparison between the multiplexer shown in Fig. 18 and a four-channel C-band input multiplexer realized using conventional dielectric resonator technology.

significant cost reduction for satellite systems. It could also provide performance discrimination not attainable with other technologies. However, convincing satellite prime contractors to consider HTS as an alternative technology for new systems would require: 1) demonstration and validation of HTS equipment integrated with highly reliable cryo-cooler in operating environment; 2) demonstration of significant cost saving for overall systems costs including cost of cryo-cooler; and 3) demonstration of performance discriminators available only with HTS technology. These represent essential steps in bridging the transition from R&D to commercial viability of HTS technology.

The Naval Research Laboratory (NRL) HTSSE program has been a harbinger in addressing these commercialization imperatives. The program has provided a sharp focus in addressing all aspects of HTS technology especially those that pertain to performance in space environment. A variety of HTS equipment, developed under HTSEE-II, is scheduled to fly on the ARGOS satellite in June 1996. Successful completion of the HTSSE program would be a big step forward in the continued development of this technology.

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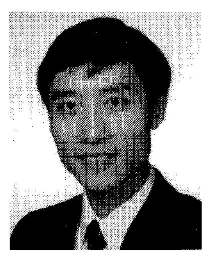

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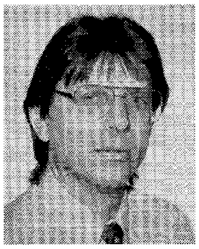

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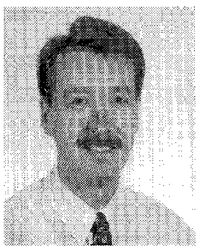

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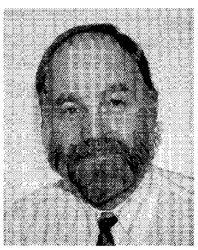

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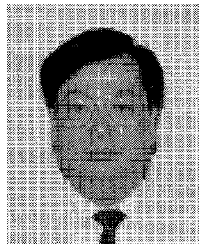

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