A 60-Channel Superconductive Input Multiplexer Integrated with Pulse-Tube Cryocoolers

Raafat R. Mansour, *Senior Member, IEEE*, Shen Ye, *Member, IEEE*, Bill Jolley, Glenn Thomson, Soeren F. Peik, *Member, IEEE*, Tony Romano, *Member, IEEE*, Wai-Cheung Tang, *Senior Member, IEEE*, Chandra M. Kudsia, *Fellow, IEEE*, Ted Nast, Brian Williams, David Frank, David Enlow, George Silverman, Jeffery Soroga, Charles Wilker, Joseph Warner, Shyam Khanna, Guy Seguin, and Gilles Brassard, *Member, IEEE*

Invited Paper

***Abstract*—This paper presents the measured results of a C-band 60-channel superconductive input multiplexer integrated with pulse-tube space-qualified cryocoolers. The multiplexer is developed to duplicate the requirements of the INTELSAT 8 program. The channel filters are self-equalized ten-pole high-temperature superconductor (HTS) planar structures designed with drop-in cryogenic ferrite circulators and isolators. This paper presents details on RF design, packaging, and cryocooler integration, as well as an assessment of overall reliability of using HTS equipment in a space environment. This paper demonstrates that at least 50% reduction in mass and 65% reduction in size can be achieved by replacing the INTELSAT 8 C-band dielectric-resonator input multiplexer with a superconductive multiplexer.**

***Index Terms*—Channel bank filters, cryogenics, high-temperature superconductors, satellite applications, superconductive filters.**

I. Introduction

THE mass and volume of payload electronic equipment is a significant contributor to the overall cost of space systems. The high-temperature superconductor (HTS) technology offers the potential of a tenfold miniaturization of payload electronic equipment leading to an overall cost reduction and accelerating the development of small satellite systems. It also represents the potential of performance enhancements of strategic value to future defense, communications, and surveillance systems. Table I summarizes the potential impact of HTS technology on satellite systems.

Over the past years, the feasibility of building HTS satellite subsystems that are small in size and mass has been demonstrated [1]–[4]. Although the reduction in mass and size is quite impressive, it is not sufficient to convince satellite prime contractors and service providers on the viability of the HTS technology for satellite systems. It has been well recognized that demonstration and validation of HTS subsystems integrated with highly reliable cryocoolers is an essential step for insertion of HTS technology in satellite systems.

A consortium consisting of COM DEV Ltd., Cambridge, Ont., Canada, Lockheed-Martin Advanced Technology Center (LM-ATC), Palo Alto, CA, Lockheed-Martin Communication and Power Center (LM-CPC), Newton, PA, and DuPont, Wilmington, DE, has been formed to develop and space-qualify integrated HTS subsystems for satellite payloads. The consortium is managed by the NASA John H. Glenn Research Center, Cleveland, OH, and is funded by the Defense Advanced Research Projects Agency (DARPA), Technology Reinvestment Program (TRP), Canadian Space Agency (CSA), and the Canadian Department of National Defense (DND).

This consortium brings together industry leaders in satellite payload equipment, HTS materials, and space cryocoolers. The program is set to develop two space-qualifiable HTS satellite-communication subsystems over a three-year period. These two subsystems are intended to serve as a benchmark for satellite prime contractors to consider HTS as a competing technology for their new space systems.

Several system studies have been carried out in the early stage of the program to determine the subsystems that would benefit most from the HTS technology. The focus of these studies has been on HTS technology maturity, performance enhancement, and economic and market factors. The following two subsystems have been selected: 1) a 60-channel HTS multiplexer that duplicates the requirements of the INTELSAT 8 program and 2) a Ka-band Beam*Link [5] subsystem that duplicates the typical requirements of multimedia satellites.

It is the objective of this paper to present the design and measured results of the 60-channel HTS multiplexer. This paper will

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R. R. Mansour was with the Corporate Research and Development Department, COM DEV Ltd., Cambridge, Ont., Canada N1R 7H6. He is now with the Electrical Computer Engineering Department, University of Waterloo, Waterloo, Ont., Canada N2L 3G1.

S. Ye, B. Jolley, G. Thomson, S. F. Peik, T. Romano, W.-C. Tang, and C. M. Kudsia are with the Corporate Research and Development Department, COM DEV Ltd., Cambridge, Ont., Canada N1R 7H6.

T. Nast, B. Williams, D. Frank, D. Enlow, G. Silverman, and J. Soroga are with the Lockheed-Martin Corporation, Palo Alto, CA 94304-1191 USA.

C. Wilker is with DuPont, Wilmington, DE 19880-0708 USA.

J. Warner is with the NASA John H. Glenn Research Center, Cleveland, OH 44135 USA.

S. Khanna is with The Canadian Department of National Defence, Ottawa, Ont., Canada K1A 0K2.

G. Seguin and G. Brassard are with the Canadian Space Agency, St. Hubert, P.Q., Canada J3Y 8Y9.

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TABLE I
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.

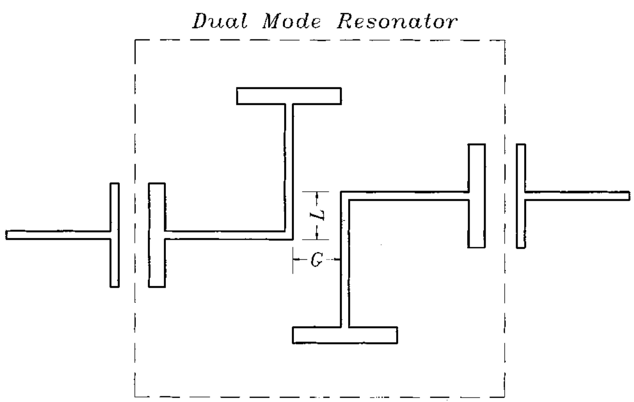

Fig. 1. Dual-mode planar resonator.

also address in detail the RF design of the input channel filters, packaging, and cryocooler integration issues as well as reliability analysis of the HTS materials for space environments.

II. INPUT CHANNEL FILTERS

The input channel filters for the INTELSAT 8 program are required to comply with stringent passband characteristics. A ten-pole self-equalized quasi-elliptic HTS planar filter has been chosen to meet these requirements. An efficient way to realize the elliptic function response and the self-equalization is to use dual-mode resonators, which, in turn, allows coupling between nonadjacent resonators to be easily realized. Over the past years, several papers have been reported on the use of dual-mode patch resonators to design elliptic function HTS filters [6], [7]. However, one major concern with patch resonators is the difficulty in eliminating the undesired coupling between the various resonator elements. This, in turn, makes it difficult to realize filters with symmetrical frequency characteristics.

In this paper, we present a novel configuration for a lumped-element HTS filter [8]. The basic resonator is shown in Fig. 1. One can consider this structure as a dual-mode resonator where coupling between the two modes is controlled by adjusting the spacing G and the offset L. The advantage of this resonator configuration is the ease of realizing and controlling the cross-coupling, which is necessary to realize quasi-elliptic and self-equalization functions. For example, Fig. 2 illustrates an eight-pole filter realized using the resonator configuration shown in Fig. 1. This filter consists of four dual-mode resonators. The filter layout permits easy realization of the cross-coupling $M14$ and $M58$. The sign of coupling, positive or negative, can be controlled by selecting the length of the coupling elements as well as the gaps: $S1$, $S2$, $S3$, and $S4$.

The dual-mode resonator shown in Fig. 2 is used to construct the ten-pole self-equalized input channel filter for the 60-channel HTS multiplexer. Fig. 3 illustrates a schematic diagram of the input channel filter. The filter is integrated with an input circulator and output isolator. The circulator is part of the multiplexer function and used for channel dropping, while the isolator is inserted at the output to isolate the filter from any mismatch. The drop-in ferrite components were designed specifically for operation at cryogenic temperatures.

The measured isolation and group delay performance of a standalone filter with a channel dropping circulator and an output isolator is given in Figs. 4 and 5. The typical specification requirements of the INTELSAT 8 program are also marked on these two figures. It can be seen that the filter exhibits symmetrical frequency characteristics. The measured performance meets the typical requirements of C-band input multiplexers. The RF test results of the integrated multiplexer are given in Section IV.

III. HTS MULTIPLEXER PACKAGE DESCRIPTION

The 60-channel HTS multiplexer is designed to duplicate the requirements of the INTELSAT 8 program. The engineering model (EM) of the 60-channel HTS multiplexer has four operational channel filters and 56 dummy filters. The bandwidths of the four operational channels are 34, 41, 72, and 112 MHz. These bandwidths were selected to correspond to all possible channel bandwidth requirements of the INTELSAT 8 program. The 56 dummy filters were inserted in the package to simulate the mass, size, and heat load of an entire 60-channel system.

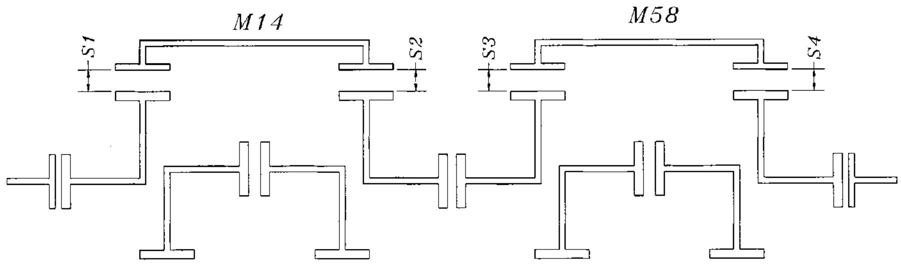

Fig. 2. Eight-pole dual-mode planar filter.

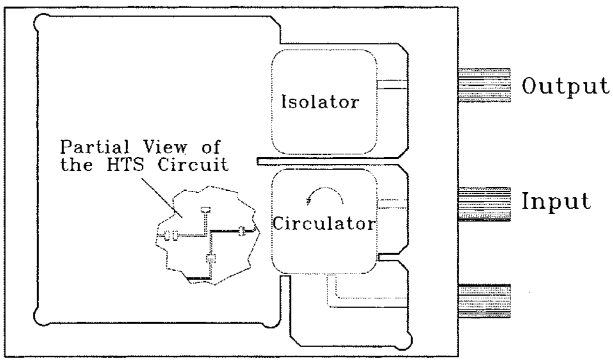

Fig. 3. Schematic diagram of the input channel filter.

All four operational filters and 56 dummy filters were mounted in six stacks of ten filters each to an aluminum support structure. Fig. 6 illustrates the filter support structure. This structure was machined from a single block of 6063 aluminum in order to increase its stiffness by eliminating bolted interfaces and decrease the thermal resistance through the filter stacks. The aluminum alloy 6063 was chosen for its high strength at room temperature and its high thermal conductivity at the filter operating temperature (77 K). The structure was designed to provide a resonant frequency of 100 Hz and provide a maximum temperature difference along a ten-filter stack of 1 K.

In the center of this aluminum structure, a beryllium shrink-fit plug was epoxied to the aluminum. This plug served as the thermal interface point between the cold head of the pulse-tube cryocooler and the components to be cooled. A matching machined copper cup, connected to the cold tip of the cryocooler via copper flexible thermal braids, would slide over this plug when the system was at room temperature. The edges of the cup and the tip of the rounded plug were flared out allowing for a blind-hole interface. This shrink fit interface was designed to seize at approximately 200 K.

The package has ten inputs and 60 outputs. A low-temperature connector plate with 70 SMA connectors is securely mounted on the filter support structure. The purpose of the connector plate was to intercept parasitic heat leaks from the coax cables that connect to the warm environment; intercepting the heat at this point allows the aluminum structure to intercept the heat and minimizes the heat load to the filter packages. Copper coax cables with an outside diameter of 0.141 in were used to connect the filters to the cold connectors and to provide the channel dropping function between filters.

The design of coaxial cables that connect the cryogenic package to the room-temperature environment is a tradeoff between heat leak and RF attenuation. An RF engineer, seeking to minimize the signal loss, will design a cable that is as short as possible, as large a diameter as possible, and is constructed of highly conductive materials (such as copper or silver). In contrast, the thermal engineer will strive to make the cable as long and thin as possible, while constructing the cable from lossy low thermal-conductivity materials (such as stainless steel) in order to reduce the heat leak. For the input multiplexer system, the compromise solution was to use a very thin-walled cable with a length that is based on the maximum allowable attenuation.

Very small diameter "lossy" coax cables were used to transition from the cold connectors to the warm connectors. Sixty 0.020-in outer-diameter stainless-steel cables served as the outputs from each filter and ten 0.034-in outer-diameter stainless-steel cables served as the inputs to each set of six filters. These small cables provided an acceptable RF loss while minimizing the parasitic heat leak into the cold package. In order to pass through the multilayer insulation (MLI) blanketing, the 70 cables were bundled into four groups, each bundle being about 1-in long, thus minimizing the number of MLI penetrations, as shown in Fig. 7.

The aluminum filter structure and filter packages were in turn mechanically supported by a G-10 fiberglass tube support system. One end of this support system was attached to a mounting plate that simulated a spacecraft interface, while the other end was attached to the inside of the aluminum filter support at approximately its center of mass. This support structure was engineered to survive the vibration environments and acceleration levels that are typical during the launch of a communication satellite.

A cylindrical aluminum shroud, approximately 0.030-in thick, surrounded the cold packaging and provided a mounting surface for the MLI blanketing. This shroud was designed with vent holes at the corners to allow the contained gases to vent during pump down. The vent holes in the shroud's corners were aligned with the seams in the MLI blanketing. Thirty layers of MLI, each layer consisting of doubly aluminized mylar and silk netting, were applied over the entire cold packaged and formed a blanket thickness of approximately 0.8-in thick.

The pulse-tube cryocooler used for this package is a miniature pulse tube developed by Lockheed-Martin-ATC [9]. The cold package was outfitted with two silicon diode temperature sensors and seven differential thermocouples (DTC's). One diode was mounted at the bottom aluminum

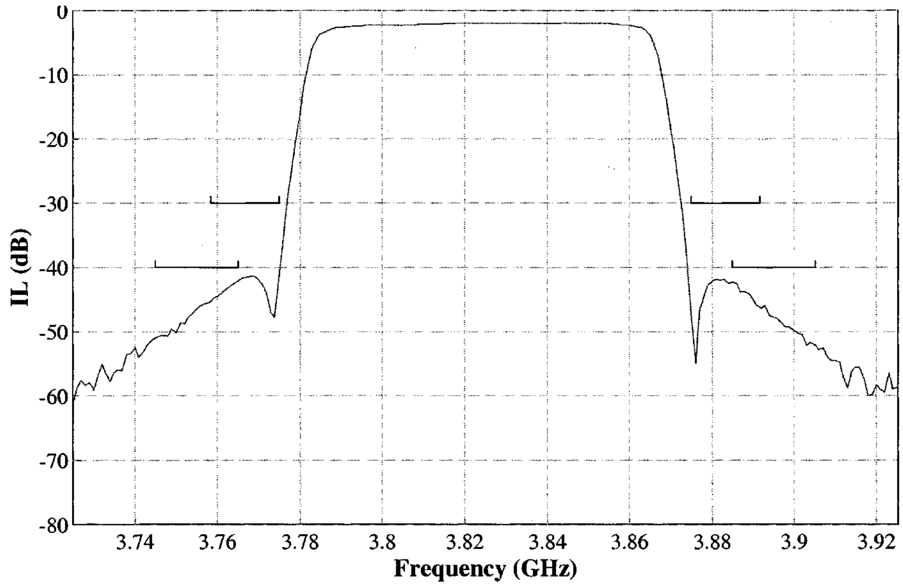

Fig. 4. Measured isolation performance of a ten-pole self-equalized planar HTS filter.

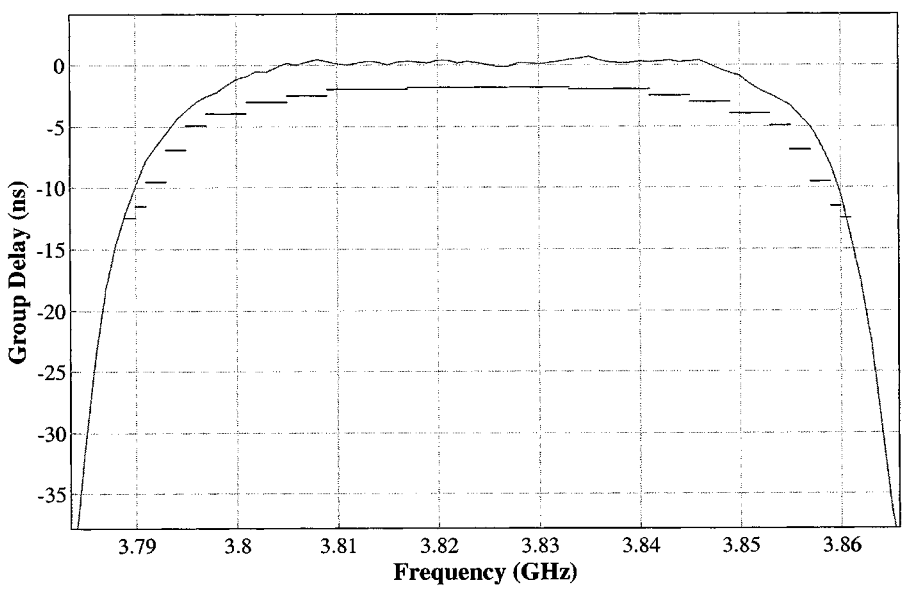

Fig. 5. Measured group-delay performance of a ten-pole self-equalized planar HTS filter.

structure near the shrink–fit interface with the cryocooler and the other was mounted at the top of the structure near the cold connector plate; the difference between these two diodes gives the maximum temperature drop along the filter stacks. Three DTC's were mounted on filter packages at the top of the stack, approximately 120° apart from each other around the circumference. Two DTC's were mounted on filter packages at the bottom of the stack and one DTC was mounted near the beryllium shrink–fit plug. The remaining two DTC's were mounted near the diodes for reference.

IV. HTS Multiplexer RF and Thermal Test Results

Under this program, two units are to be built for the 60-channel HTS multiplexer, an EM and a qualification model (QM). In this section, we present the results for the EM model. Fig. 8 illustrates the RF performance of the four-channel multiplexer at 77 K. As an integrated package, the absolute loss of the individual channels is much higher. The overall absolute loss is the sum of the filter insertion loss, loss of the input/output cables, loss of the output isolator, and loss of the channel dropping circulators. It should be noted that the absolute insertion loss is not a constraint for input multiplexer applications since input multiplexers follow the front-end low-noise amplifiers in satellite payloads. The filter Q, however, is of extreme importance since it determines the passband characteristics of the channel filter. In this EM, some of the operational channel filters were built using single-sided TBCCO, while the others were built using double-sided TBCCO wafers. This explains the variation shown in Fig. 8 for the insertion loss absolute value. The channel filters for the QM will be built using double-sided wafers and are

Fig. 6. Sixty filters mounted to the aluminum support structure. Also shown is the fiberglass support tube in place and the cold coax connectors.

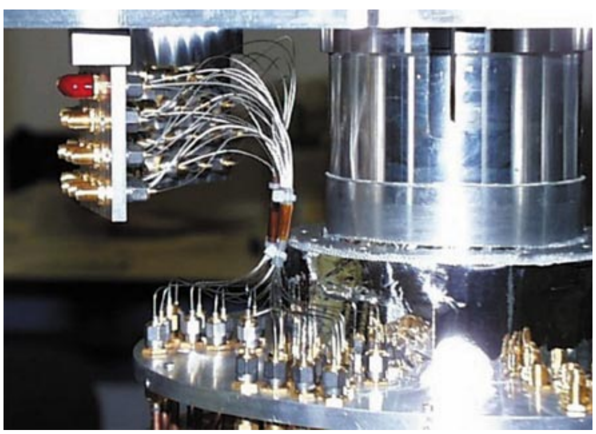

Fig. 7. Close-up of the small-diameter stainless-steel coax cables routing from the warm connectors to the cold connectors. Note the bundling of the cables.

expected to have a much better performance than that shown in Fig. 8 for the EM model.

The EM system of the 60-channel input multiplexer was inserted into a vacuum bell jar, as shown in Fig. 9, and turbo pumped at a slow controlled rate to a 2×10^{-6} torr vacuum. Once the vacuum was achieved, liquid nitrogen was used to rapidly pre-cool the package to about 85 K. The liquid nitrogen flowed through Teflon tubes, connected to a heat exchanger loop epoxied to the center of the aluminum filter support structure. Without the use of liquid nitrogen, a much longer cool-down time would be needed than with just the pulse-tube cryocooler. After the package had reached 85 K, the flow of liquid nitrogen was stopped, and the pulse-tube cooler was turned on to continue the cool down.

Two days were required to cool the package from 85 to 77 K. During the cool down, and for two weeks of continuous operation thereafter, the cooler showed no sign of performance degradation, easily maintaining the package temperature near 77 K. The LN2 pre-cool is used for ground testing only. On orbit, using only the cryocooler, it would take approximately one week for the package temperature to reach 77 K using only the cryocooler.

RF test data were taken at four temperatures. The temperatures at which this testing was performed are shown in Table II. This table also shows the temperature read by the bottom and top diodes. Fig. 10 illustrates the measured RF performance of Channel 1 at 77.1, 82.3, and 85.2 K, respectively. It is observed that the filter performance drifts by 2 MHz over a temperature change of 7.1 K, i.e., a temperature drift of roughly 300 kHz/°.

The channel filters are designed with $\pm$0.6- to $\pm$ 0.9-MHz margin. This allows a minimum temperature margin of approximately 2 K. It can be seen from Table II that the maximum temperature difference experienced along the filter stacks was less than 0.5 K. Considering the fact that the cryocooler temperature variation is $\pm$0.1 K, the overall temperature variation within the package is well within the maximum allowable temperature difference of 2 K.

Table III shows a comparison of the predicted heat leak rate with the measured heat leak rate, as inferred from the cryocooler input power. The "Design" heat leak rates are based on the 70 small-diameter coax cables having a very low emissive (0.03) outer surface. Also, it was assumed in the design that the MLI blanket would be 1-in thick and consist of 37 layers. As built, the 70 small coax cables had only their normal stainless-steel outer surface (assumed emissivity of 0.2) and the MLI blanketing was only 0.8-in thick with 30 layers. Once again, the QM model is expected to have lower heat load than that given in Table III for the EM model.

V. Benefits of HTS Technology for Input Multiplexers

The current technology for C-band input multiplexers is the dielectric-resonator technology. This technology was used to build the C-band input multiplexers for all satellites under the INTELSAT 8 program. COM DEV Ltd. built all the C-band input multiplexing equipment for this program, which, in turn, was integrated into the spacecraft by the Lockheed-Martin Corporation.

Fig. 11 illustrates a comparison between the ten-pole self-equalized HTS planar filter and the ten-pole self-equalized dielectric-resonator filter similar to the one used in INTELSAT 8. Table IV summarizes the overall mass saving and size reduction. It can be seen that more than 50% reduction in mass and 50% reduction in size can be achieved with the use of HTS technology.

A detailed benefit analysis model was developed to assess the impact of inserting HTS technology into satellite communication systems. The analysis is driven by the additional revenue generated by extending mission life. The lifetime extension results from the mass reduction produced by the HTS technology. Since the revenue generated by mass savings occurs only at the

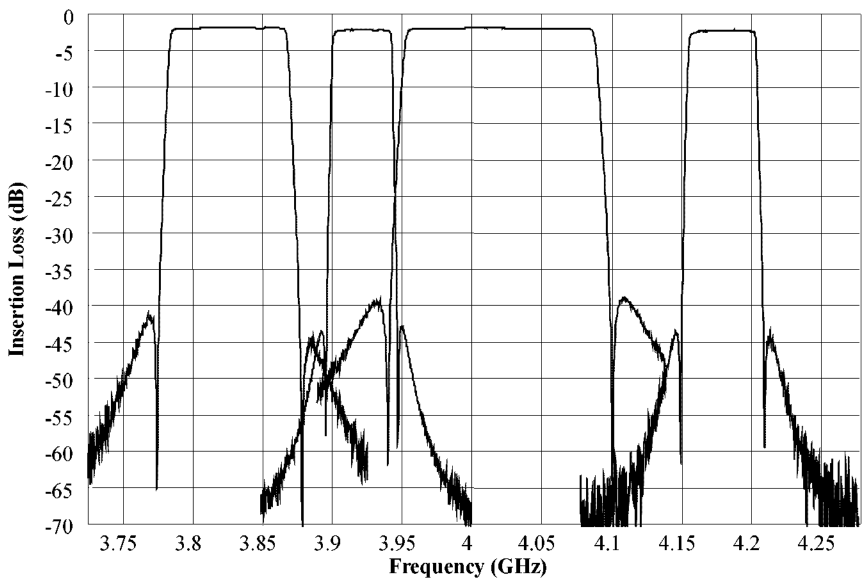

Fig. 8. Measured RF performance of the EM four operational RF channels as measured individually.

Fig. 9. Sixty-channel HTS input multiplexer and integrated pulse-tube cryocooler inside the vacuum bell jar for testing.

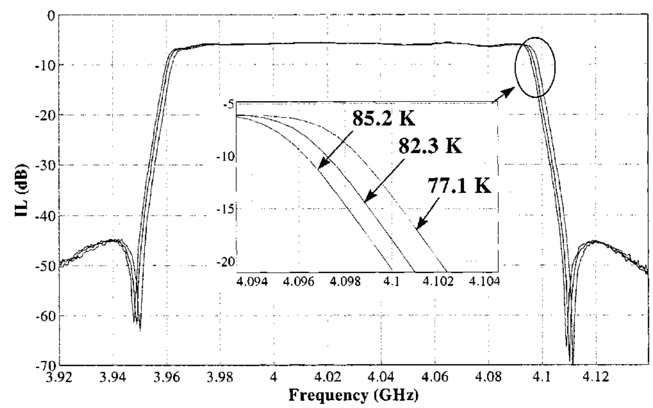

Fig. 10. Measured RF performance of Channel 1 at 77.1, 82.3, and 85.2 K.

TABLE II
SUMMARY OF DIODE TEMPERATURES AT POINTS WHERE RF DATA WERE TAKEN

Cold Tip Diode (K)	Bottom Diode (K)	Top Diode (K)
73.8	76.7	77.1
75.9	78.5	78.8
79.1	82.2	82.3
82.2	85.1	85.2

TABLE III
SUMMARY OF PREDICTED AND MEASURED PARASITIC HEAT RATES

Component	Heat Leak rate (W)	
	Design	As-Built
Coax Cables	0.323 W	0.425
MLI/Insulation	0.246 W	0.314
Fiberglass supports	0.228 W	0.228
Total	0.797 W	0.967 W

end of life, the benefit of the technology insertion is evaluated in terms of its net present value (NPV). The NPV is the current value of an investment due to future cost reductions. The results for the 60-channel multiplexer are presented in terms of the internal rate of return (IRR). The IRR is the rate for which the NPV would be zero.

Fig. 12 shows the IRR trade for an HTS C-band multiplexer operating in geo-stationary orbit. The cost benefit analysis uses a typical annual volume of ten multiplexers and cryogenic coolers and projected HTS production costs. The figure shows the IRR as a function of the mass reduction and mission life

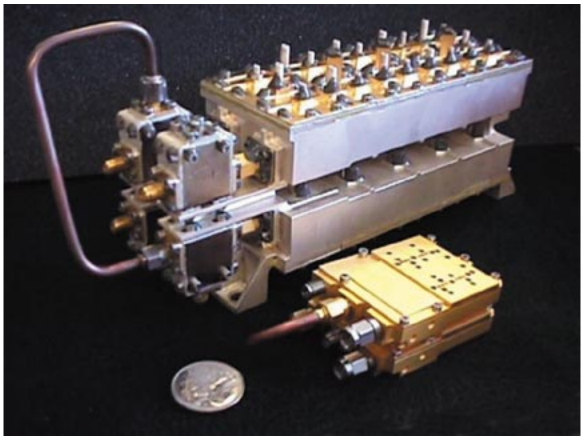

Fig. 11. Comparison between a ten-pole self-equalized HTS planar filter and a ten-pole self-equalized dielectric resonator filter.

extension. The abscissa is mass reduction per space vehicle and the right-hand-side axis is mission life; the IRR is indicated by the shaded segments. As an example, a mass reduction of 10 kg and a two-year life extension from 10 to 12 years, results in an IRR of 15% to 20% while a reduction of 16 kg produces an IRR (20% to 25%).

The system considered in this paper has 60 channels. Future multimedia satellites are expected to have a larger number of RF channels [5]. As the number of channels increases, the benefits of inserting the HTS technology become more substantial.

VI. Reliability of HTS-Based Subsystems in Space Environment

Manufacturers of electronic systems for space are by nature a conservative group. Before any new technology can be inserted into a satellite, it must be extensively studied and the potential failure mechanisms well understood. Reliability is an important consideration in satellite system design.

The environmental performance specifications for an electronics payload of a typical satellite are a combination of diverse requirements. The payload is often exposed to years of ambient conditions during shipment, spacecraft integration, and testing and launch-pad operations. For example, a satellite sitting on the launch pad in the hot Florida sun may experience temperatures up to 80 °C with up to 70% relative humidity (RH) levels. During launch, the payload is severely shaken and also experiences rapid decompression upon achieving orbit. Once in space, high-energy particles may damage critical components. After all of this, the HTS-based cryoelectronics must still meet a long list of exacting electrical operating performance requirements all with a 5–15-year expected lifetime.

Ultimately, however, it is the reliability of the entire integrated HTS-based cyroelectronics payload that is required. Not all of the components of every electronics payload are fully exposed to the full environmental specifications. For example, many digital devices are radiation sensitive. The reliability of these type of devices is increased by using special radiation hardening techniques, by designing in redundancy and by providing additional shielding in the device package. It is, therefore, important to understand the reliability limitations of the HTS material, of patterned HTS devices, and of packaged HTS-based cryoelectronics. In this way, a payload containing HTS-based cryoelectronics can be made reliable.

The reliability of HTS materials involves not only the HTS, but also the crystalline substrate. The important electric property of the HTS is the surface resistance, and for the substrate is the dielectric constant and loss tangent. The stability of these electrical properties upon rapid thermal cycling, thermal exposure, humidity exposure, vacuum exposure, and radiation exposure need to be studied. In addition, the adhesion between HTS and the substrate also needs to be studied.

The reliability of patterned HTS devices involves not only a patterned HTS device, but also the normal metal contacts and wirebonds. A simple easily characterized device for studying the reliability is a two-port resonator. The important electrical properties of an HTS resonator are the resonant frequency and unloaded Q-value, and for the normal metal contacts is the contact resistance. The stability of these electrical properties upon rapid thermal cycling, thermal exposure, humidity exposure, vacuum exposure, and radiation exposure need to be studied. In addition, the adhesion between the HTS, normal metal contacts, and wirebonds also needs to be studied.

The reliability of packaged HTS-based cryoelectronics involves not only the package, but also the epoxies, solders, and wirebonds. A simple easily characterized device for studying the reliability is a four-pole resonator. The important electrical properties of an HTS filter are the center frequency, bandwidth, in-band insertion loss, return loss, and out-of-band rejection. The stability of these electrical properties upon rapid thermal cycling, thermal exposure, humidity exposure, vacuum exposure, radiation exposure, and vibration need to be studied. In addition, the adhesion between the HTS device, connectors, package, and the wirebonds also needs to be studied.

A thorough reliability analysis of HTS materials and devices for space applications has been carried out under this TRP program. The following subsections present some of the qualification test results.

A. Rapid Thermal Cycling

A 2-in-diameter wafer was placed in a Teflon holder and rapidly immersed into a Dewar of liquid nitrogen. The sample cooled from room temperature to 77 K in approximately 12 s. The wafer was then removed and placed in a large plastic bag, which was being flushed with room-temperature dry nitrogen. The sample warmed back to room temperature in about 1 min. No condensation was observed on the wafer. The wafer was visually inspected for signs of substrate cracking, delamination of the passivation layer or delamination of the HTS from the substrate. This process was repeated a total of three times. The R_s of the wafer was then remeasured in the HTS sapphire resonator. No reliability problem was observed with either of the HTS materials, TBCCO or YBCO on $LaAlO_3$, or with any of the passivation coatings, PMMA, or TeflonAF.

B. Thermal Exposure

A 2-in-diameter wafer was placed in a thermal chamber and exposed to 80 °C in dry nitrogen for four weeks. No reliability problem was observed with either of the HTS materials,

TABLE IV
COMPARISON BETWEEN DIELECTRIC-RESONATOR TECHNOLOGY AND HTS TECHNOLOGY FOR A 60-CHANNEL HTS 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 EM Model	15.2 kg	24×10^{-3} m^3
HTS technology including packaging, two cryo-coolers and two electronic-controllers QM Model (projected)	12.2 kg	24×10^{-3} m^3
Percentage Saving	> 50 %	> 50 %

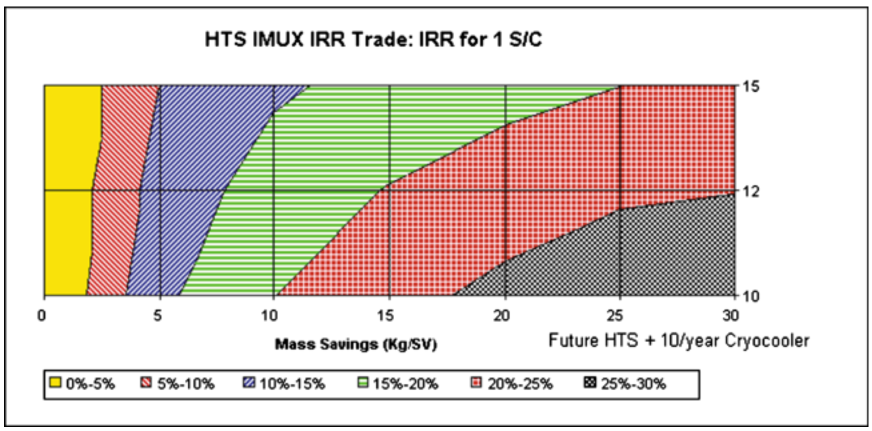

Fig. 12. IRR as a function of mass reduction and mission life extension.

TBCCO or YBCO on $LaAlO_3$, or with any of the passivation coatings, PMMA, or TeflonAF.

C. Humidity Exposure

A 2-in-diameter wafer was placed in a thermal chamber and exposed to 70% RH at 60 °C for three weeks. All of the HTS material on the surface of the substrate decomposed leaving a residue composed primarily of the component oxides. Two wafers were inserted in packages sealed by epoxy. The packages were then exposed to 80% RH at 60 °C for 12 days. A measurable increase in the surface resistance has been observed, however, the wafer remained in the superconductive state.

It will be necessary to protect HTS-based cryoelectronics from humidity exposure either by using passivation or by hermetically sealing the packages.

D. Vacuum Exposure

The reliability of HTS material under long-term vacuum exposure is not known. This might be a problem especially for YBCO, which has been known to lose oxygen, thus depressing the T_c. It is not clear that an environmental test that accelerates the oxygen loss at temperatures above the operating temperature occurs by the same failure mechanism.

E. Radiation Exposure

A 2-in-diameter wafer was diced into four pair of 12-mm-square pieces. The critical temperature T_c of each wafer was measured using an eddy current measurement. Each pair was also characterized in the 27.5-GHz resonator from 50 K to T_c in 5-K steps. The R_s value measured is just the average value of the two samples. The samples were then grounded and exposed to a total fluence of 1×10^{16} 1.5-MeV protons. The T_c and the R_s were remeasured. A small measurable degradation of the T_c was observed ranging from 1 to 3 K. The small degradation of the R_s near the T_c could be explained completely by the depressed T_c. The effect of patterned and packaged HTS-based cryoelectronics will need to be studied further.

VII. CONCLUSIONS

We have successfully demonstrated the feasibility of building a C-band HTS multiplexer that duplicates the requirements of the INTELSAT 8 program. The multiplexer is integrated with two miniature pulse-tube cryocoolers to meet the reliability requirement of space applications. The whole package is designed to be in the form of "plug-and-play" to replace conventional C-band dielectric-resonator input multiplexers inside the INTELSAT 8 satellites. The results achieved in this paper illustrate that an overall mass saving of 12 kg (approximately 50% saving) and a size reduction of over 50% can be achieved with the use of HTS technology.

This paper has also presented the layout of a novel design for a dual-mode planar HTS resonator that makes it easy to construct self-equalized filters with symmetrical frequency characteristics. Both RF and thermal results are presented for the integrated package. The results show that the maximum temperature difference experienced along the cryogenic package is well within the design margin of the input channel filters.

The work done under this TRP program completes an important step toward the commercialization of HTS technology for space applications. The HTS multiplexer presented in this paper demonstrates that HTS technology can be implemented into operational space systems with a convincing advantage over current conventional technologies.

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Raafat R. Mansour (S'84–M'86–SM'90) 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, Ont., Canada, in 1986, all in electrical engineering.

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

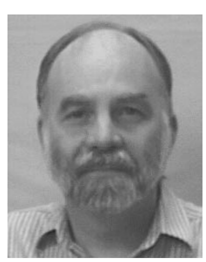
Shen Ye (S'88–M'92) was born in Shanghai, China. He received the B.Eng. and M.Eng. degrees from the Shanghai University of Technology, Shanghai, China, in 1982 and 1984, respectively, and the Ph.D. degree from McMaster University, Hamilton, Ont., Canada, in 1991, all in electrical engineering.

From 1984 to 1986, he was with the Department of Electrical Engineering, Shanghai University of Technology. In 1991, joined Optimization Systems Associates Inc., Dundas, Ont., Canada. He implemented microstrip components for the CAD package osa9O/hope. He developed Empipe, which connects an electromagnetic-field solver to osa9O/hope. In 1993, he joined COM DEV Ltd., Cambridge, Ont., Canada, where he is currently a Principle Member of Technical Staff. His current work includes RF MEMS and microwave thin-film circuit design; in particular, high-temperature superconductive thin-film filter and multiplexer design. He has also developed various application-specific CAD programs.

Dr. Ye was the recipient of a 1991 Industrial Research Fellowship presented by the Natural Sciences and Engineering Research Council of Canada.

Bill Jolley was born September 4, 1967, in Toronto, Ont., Canada. He received the B.S. degree (with honors) in electronics engineering technology from the DeVry Institute of Technology, Columbus, OH, in 1992.

Since joining COM DEV Ltd., Cambridge, Ont., Canada, in 1993, he has been involved in the development of HTS microwave devices for space applications. His experience in the HTS field encompasses devices that employ hybrid dielectric resonator and thin-film technology for both high- and low-power microwave applications.



Glenn Thomson was born in Montreal, P.Q., Canada. He received the degree in mechanical engineering from Concordia University, Montreal, P.Q., Canada.

In 1986, he joined COM DEV Ltd., Cambridge, Ont., Canada, where he has designed microwave equipment for a number of commercial communications satellites. In 1992, he joined COM DEV's Corporate Research and Development Department, where he has been involved with a number of wireless, satellite, and superconducting filter programs. He holds several patents for microwave switches and filters.

Mr. Thomson is a Registered Professional Engineer.

Soeren F. Peik (M'96) received the electrical engineering diploma from the University of Hannover, Hannover, Germany, in 1994, and the Ph.D. degree in Microwave engineering from the University of Waterloo, Waterloo, Ont., Canada, in 1999.

During 1994, he was with the German Aerospace Research Establishment (DLR) Oberpfaffenhofen, where he was involved with the development of planar antenna beam⁄forming net⁄works. In 1996, he joined the Corporate Research and Development Department, COM DEV Ltd., Cambridge, Ont., Canada, where he is currently involved in the development of superconductive microwave circuits and MEMS microwave devices for space applications. His main research interests also include the effective design and optimization of passive and active microwave circuits as well as MEMS microwave circuits. He has authored or co-authored over 15 papers in the area of microwave and aerospace engineering.

Tony Romano (M'90), photograph and biography not available at time of publication.

Wai-Cheung Tang (SM'94) was born in Hong Kong, on November 20, 1953. He received the B.Sc. and M.Sc. degrees in electrical engineering from the University of Waterloo, Waterloo, Ont., Canada, in 1980 and 1984, respectively.

In 1980, he joined COM DEV Ltd., Cambridge, Ont., Canada, as a Microwave Engineer. Since then, he has progressed through various technical and management positions, including Director of Satellite Communication Products, Director of Research and Development, and Vice President of Engineering, and is currently Vice President of Corporate Research and Development. He holds 13 patents and has authored or co-authored numerous papers in the field of microwave filters and multiplexing networks for satellite applications.

Mr. Tang is an Associate Fellow of the American Institute of Aeronautics (AIAA).

Chandra M. Kudsia (S'78–M'78–SM'93–F'00) received the B.Sc. degree in physics from Delhi University, Delhi, India, in 1961, the B.Eng. degree from the Indian Institute of Science, Bangalore, India, in 1964, the M.Eng. degree in electrical engineering from McMaster University, Hamilton, Ont., Canada, in 1966, and the Ph.D. degree in electrical engineering from Concordia University, Montreal, P.Q., Canada, in 1979.

From 1967 to 1976, he was with RCA Limited, Montreal, P.Q., Canada, where he was involved with the design and implementation of microwave filters and multiplexing networks for communications satellites and earth stations. In 1976, he joined COM DEV Ltd., Cambridge, Ont., Canada. He has served as Principal Engineer, Vice-President, and is currently Chief Scientist. His responsibilities include overseeing company wide research and development activities, participation in the planning of long-term business development, and serving on numerous national and international advisory committees. He is currently on the Board of Directors of CITO, GUARD Inc.—a publicly traded company to commercialize university research, and the Canadian Foundation for International Space University (CFISU).

Dr. Kudsia is a Fellow of the American Institute of Aeronautics and Astronautics (AIAA) and the Engineering Institute of Canada (EIC). In 1998, he received the A. G. L. McNaughton Award and Medal, presented by the IEEE.

Ted Nast, photograph and biography not available at time of publication.

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Gilles Brassard (M'89), photograph and biography not available at time of publication.