Feasibility and Commercial Viability Issues for High-Power Output Multiplexers for Space Applications

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***Abstract*—The objective of this paper is to address the issues related to the commercial viability of employing high-power high-temperature superconductor (HTS) filters and multiplexers for communication satellites. Experimental results are presented for fully integrated contiguous HTS manifold-coupled output multiplexers. Both hybrid dielectric-resonator HTS filters as well as planar HTS filters are used to construct these multiplexers. The paper provides a detailed analysis of the cooling load of HTS high-power multiplexers, and describes how it varies with the achievable filter Q and the type of I/O RF cables. It also demonstrates the role that the I/O RF cables play in determining the cooling load of HTS subsystems.**

***Index Terms*—High-temperature superconductors, microwave filters, power filters, space application.**

I. Introduction

OVER THE past four years, there has been a strong interest among researchers to develop high-temperature superconductor (HTS) filters capable of handling high power. Indeed, several papers have been published demonstrating the feasibility of building high-power HTS filters [1]–[5]. The next natural step is to demonstrate the feasibility of using these filters to construct large subsystems such as high-power output multiplexers. The problem of designing such subsystems is twofold. Firstly, the design of the HTS subsystem itself, and secondly the cryo-packaging and cryocooler integration of the subsystem.

This paper presents a detailed tradeoff analysis on packaging and cryocooler integration of HTS output multiplexers. The break-even point for mass, heat load, and dc power requirements are highlighted. Although the low-power HTS technology has been successfully deployed in commercial applications [6], [7], the discussions given in this paper outline the most important issues that which need to be addressed before one can see benefits of using high-power HTS technology in commercial applications.

In [8], results were reported on the design of a prototype model for an HTS noncontiguous output multiplexer. In this paper, we present the layout and measured data of advanced HTS contiguous output multiplexers. We also present the results of a novel high-power HTS thin-film filter employing the split-resonator concept. With the use of split resonators, the resonator current becomes more evenly distributed, leading to a filter structure that exhibits an excellent power-handling capability compared to what can be achieved using conventional HTS thin-film designs.

II. Design Considerations of High-Power Output Multiplexers

The operating power of input and output multiplexers can vary from one satellite to another. Typically, input multiplexers operate at very low power levels (milliwatts), while output multiplexers operate at 10–100 W. The type of multiplexing approach is another key parameter that differentiates input and output multiplexers. While the circulator-coupled approach is widely used in input multiplexer applications, it is seldom used in the design of output multiplexers due to its relatively poor insertion-loss performance. In [9], the measured performance of a circulator-coupled low-power superconductive input multiplexer has been presented. This paper deals with the performance and design considerations of high-power superconductive output multiplexers.

The number of channels on the manifold can range from 3 to 12 (or higher), depending on the type of services the satellite is providing. A satellite payload can consist of more than one output multiplexer. Typically, the channel filters for C-band output multiplexers are either four- or five-pole 1% bandwidth quasi-elliptic filters with two transmission zeros. In contrast to the circulator-coupled approach [9], where there is no interaction between channel filters, channel interaction is quite strong for the manifold-coupled approach. The channel filters must be properly designed to take into account the loading effects from adjacent channels.

For a four-channel output multiplexer with a channel filter average power of 50 W, the instantaneous peak power due to the combined signal on the manifold can be as high as $\text{manifold peak power} = (4)^2 \times 50 = 800$ W. In view of the extremely high peak power level, which the manifold must handle, it is not feasible to construct the manifold using

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currently available HTS materials. The manifold must then be built using conventional technology.

In superconducting output multiplexers, passive intermodulation (PIM) products could be generated from the inherent nonlinearity of the HTS materials and/or the manifold. Even though the manifold is not made of HTS materials, any microcracks or voids on the manifold can generate intermodulation products. For a typical communication satellite system, the level of any intermodulation products produced by the transmit portion of the satellite that fall within the satellite's receive band has to be at least 20 dB below the power of the received signal. This condition results in a carrier to PIM (C/I) requirement of anywhere from 140 to 200 dB depending upon the system gain and transmitter/receiver configuration. The feasibility of building high-power hybrid dielectric resonator/high-temperature superconductor (DR/HTS) filters with a third-order intercept point of more than 100 dB has been demonstrated in [1].

Multipaction and/or ionization breakdown is another problem, which could limit the power-handling capability of the superconducting high-power multiplexer. Multipaction is an electron resonance phenomenon, which takes place in components operating in atmospheric pressure lower than 10^{-5} torr. At atmospheric pressure higher than 10^{-5} torr, multipaction cannot occur since ionization is the limiting breakdown condition. However, for satellite output multiplexers, the ionization is less common than multipaction breakdown, as it requires partial pressure conditions, which are unlikely to occur in space.

Multipaction represents a possible payload failure mechanism for communication satellites since it can destroy RF components and/or significantly raise noise levels. If the superconductive channel filters are not properly designed, their power-handling capability could in fact be limited by the multipaction breakdown rather than by the inherent power-handling limitations of the HTS materials.

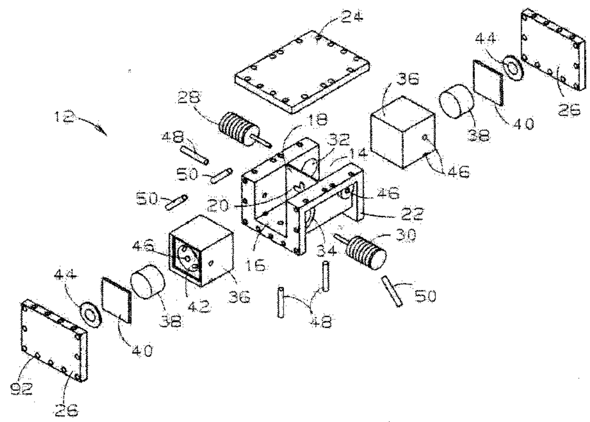


Fig. 1. Detailed configuration of a four-pole hybrid DR/HTS filter.

Fig. 2. Comparison between a four-channel superconductive manifold-coupled multiplexer and four-channel C-band output multiplexer built using conventional waveguide technology.

III. Experimental Results

A. Output Multiplexers Employing Hybrid DR/HTS Filters

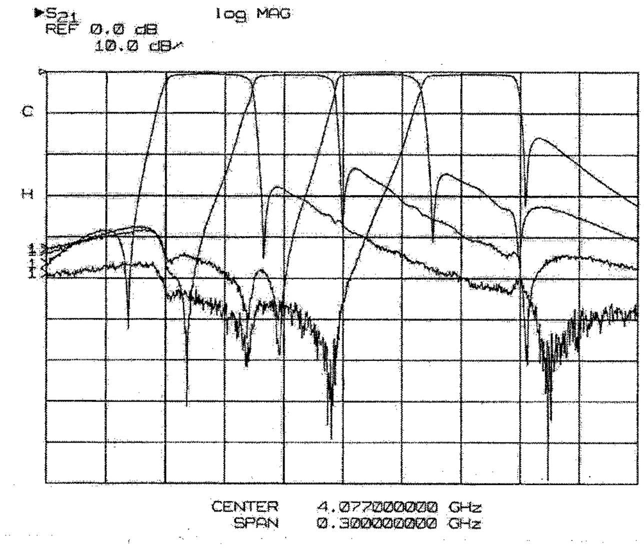
Fig. 1 illustrates a detailed configuration of a four-pole hybrid DR/HTS filter. The filter consists of two dielectric resonators operating in image-type dual modes. The resonators are supported inside the filter housing using two blocks made of low-loss low-dielectric-constant ceramic materials. The HTS material is in the form of 0.5 in $\times$ 0.5 in wafers, which are diced from the standard 2-in wafers. The HTS plates are kept in contact with the dielectric resonators using springs and metallic plates bolted to the filter housing. Both the housing and ceramic blocks have holes to allow the filter to be tuned using standard metallic screws. A detailed description of this filter is given in [10]. A description of several eight-pole versions of this filter is also given in [10].

These filters have been proven to handle extremely high power levels in the range 50–100 W [1], [8]. The insertion loss of these filters is mainly determined by the loss tangent of the dielectric resonators and the ceramic blocks as well as the surface resistance of the HTS materials. Typically, the loss tangent of the dielectric material improves at lower temperatures, which helps to improve the insertion loss of the filter. The advantages of such type of filter are as follows.

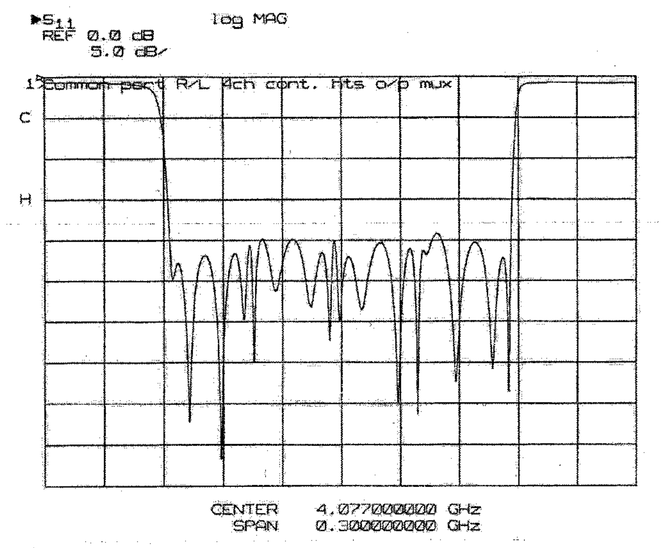
1) No etching is required for the HTS material. Etching is known to reduce the power-handling capability of the HTS material and degrade its surface resistance.
2) The filters can be easily tuned using conventional tuning screws.
3) With the use of the state-of-art low-loss dielectric resonators with high dielectric constant, such filters can be made smaller in size than their counterparts: high-power HTS thin-film filters.

The major drawback of this filter is the mechanical design complexity: the filter must be thermally stable to ensure performance repeatability as the temperature changes from cryogenic to room temperature (shipping or storage) and then back to cryogenic temperature (testing and operation).

Fig. 2 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,



(a)



(b)

Fig. 3. (a) Measured isolation performance of a four-channel C-band superconductive manifold coupled multiplexer. (b) Measured return loss performance of a four-channel superconductive manifold-coupled 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. The measured isolation and return-loss performance of this multiplexer are given in Fig. 3. The multiplexer has been tested for high power; the channel filters were capable of handling 50 W while meeting all RF performance specifications of C-band output multiplexers. A layout of a six-channel version of this multiplexer is given in Fig. 4.

B. Output Multiplexers Employing Planar Thin-Film HTS Filters

The current density is a critical parameter in designing high-power thin-film HTS filters. Over the past two years, several papers were reported [2]–[4] suggesting the use of HTS patch-type resonators operating at TM_{01} modes. One of the

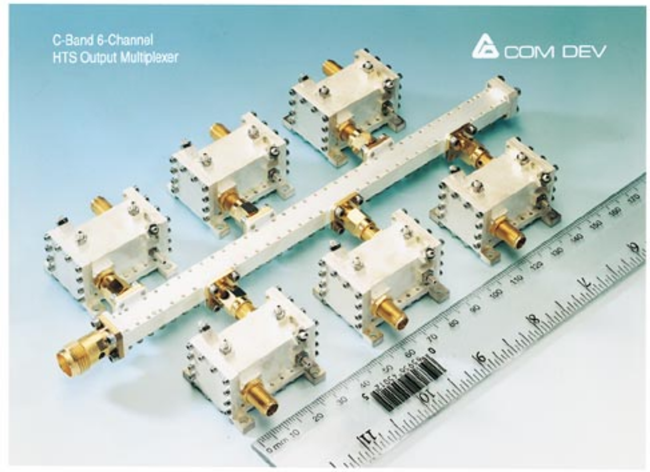
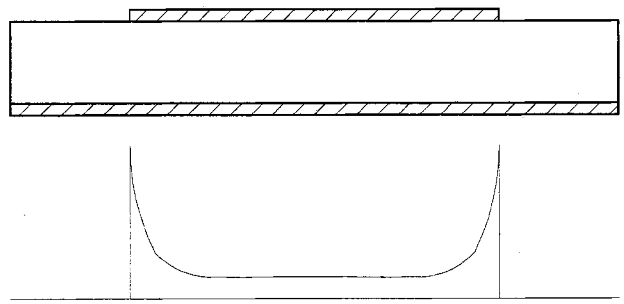
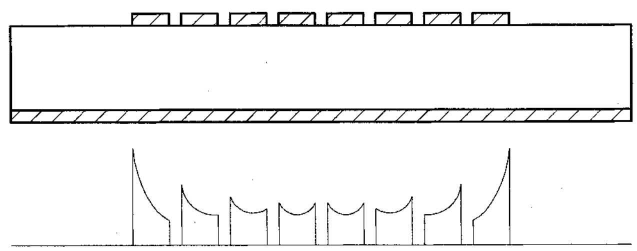


Fig. 4. Layout of a six-channel superconductive manifold-coupled multiplexer.



(a)



(b)

Fig. 5. Cross-sectional and current-density views of: (a) a solid microstrip line and (b) a microstrip line with narrow slots.

problems associated with the use of this type of resonators is that the attainable spurious performance may not be satisfactory in many applications [11]. Additionally, HTS filters built using TM_{010} patch resonators are considerably larger in size compared to conventional planar HTS thin-film filter designs.

Using a larger resonator size is a natural choice to lower the current density and, hence, increase the power-handling capability of the resonators. However, the increase of resonator size has its limitations, i.e., the resonant mode along the resonator width direction may become too close to the desired resonator mode, which, in turn, degrades the filter spurious performance. Fig. 5 shows a cross-sectional view of a conventional microstrip line and sliced microstrip lines. A schematic view of their current distribution is also illustrated on the same figure. Conventional microstrip lines have high current concentration close to

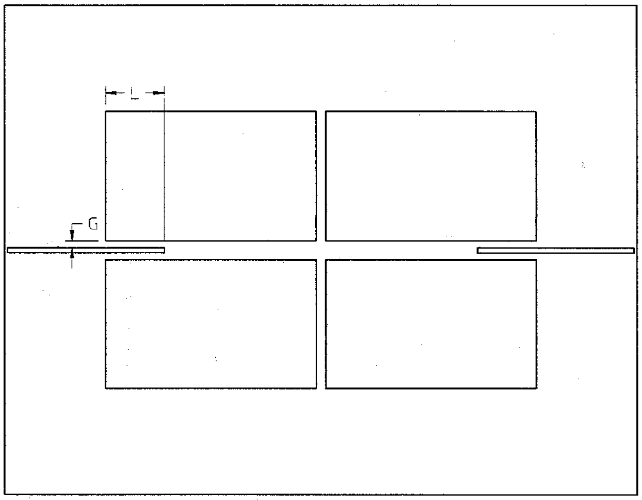
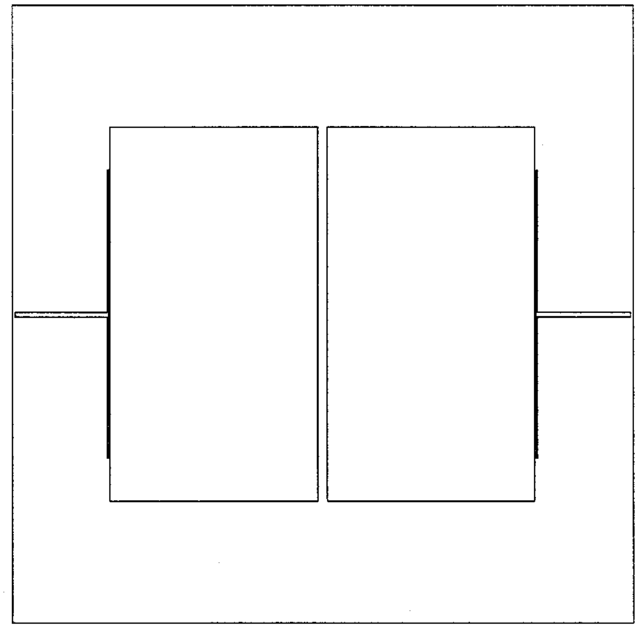
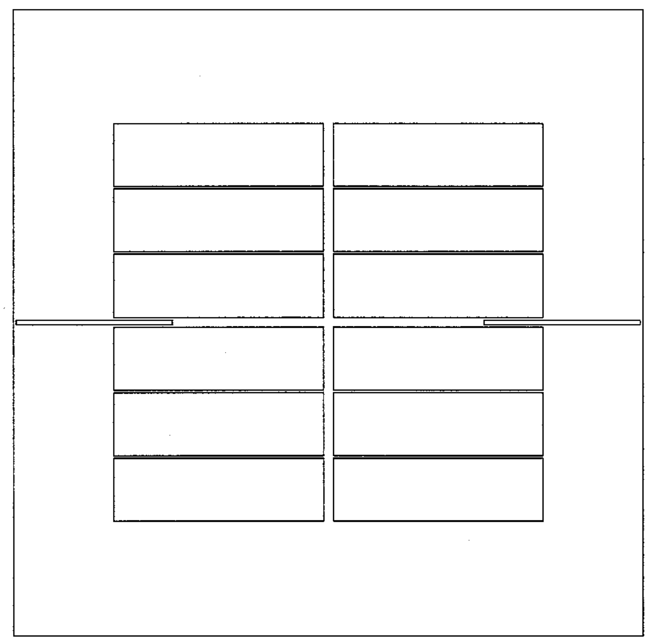


Fig. 6. Schematic microstrip filter using split resonator and inserted lines I/O coupling structures.



(a)



(b)

Fig. 7. Layout of the two-pole Chebyshev microstrip filter: (a) using conventional solid resonator and T-shaped I/O coupling structure and (b) using split resonator and inserted-line I/O coupling structure.

the outer edges. However, by using the split-resonator concept, shown in Fig. 5(b), the current redistributes itself such that the current density at outer edges is reduced while that at the inner edges is increased.

Fig. 6 shows a two-pole filter using the proposed design. Each resonator consists of two (or more) parallel pieces separated by gaps. Full-wave EM simulation [12] has shown that the resonant frequency of the split resonator is very close to that of a similar solid resonator. However, with the use of split resonators, we can reduce the peak current density at the outer edges so that the overall power-handling capability of the resonator can be improved. There is another important advantage of applying the split-resonator concept. With the same total resonator width, the resonant frequency corresponding to the width of the resonator, i.e., the mode orthogonal to the desired operating mode, can be moved much higher. In other words, a much wider resonator can now be used without the potential interference of the unwanted orthogonal mode.

Fig. 7(a) illustrates the layout of a two-pole conventional solid resonator with T-shaped I/O coupling, while Fig. 7(b) illustrates the layout of split resonator with inserted I/O coupling structure. Having split-type resonators allows extending the microstrip I/O lines into the resonator. A wide range of coupling values can be realized by adjusting the gapwidth G and inserted line length L. The parameters G and L are defined in Fig. 6. In contrast to the T-shaped coupling structure, shown in Fig. 7(a), the new I/O structure can be just a straight line with no high-current concentration spots due to discontinuities. The current plot density for the two filters is given in Fig. 8. It can be seen that the split resonator and inserted I/O lines have attracted more current toward the center of the resonator. The current distributes more evenly over the resonator cross section.

Fig. 9(a) shows a layout of a three-pole filter employing our new proposed design. The simulated current distribution is also given in Fig. 9(b). In order to further improve the power-handling capability of the filter, gold films were deposited on the high current spots of the input and output lines. It should be mentioned that the gold films deposited on the I/O lines have a little impact on the Q of the resonators, which are completely made out of HTS films. The filter was designed for 1% bandwidth on a 20-mil-thick $LaAlO_3$ substrate. The resonator dimensions are approximately 300 mil $\times$ 600 mil. Note that the effective resonator width is approximately twice the resonator length. The inserted I/O coupling line is simply an extension of the 50-Ω feed line. The filter shown in Fig. 9(a), with gold films deposited on I/O lines, has been tested for high power and has been shown to handle 35 W.

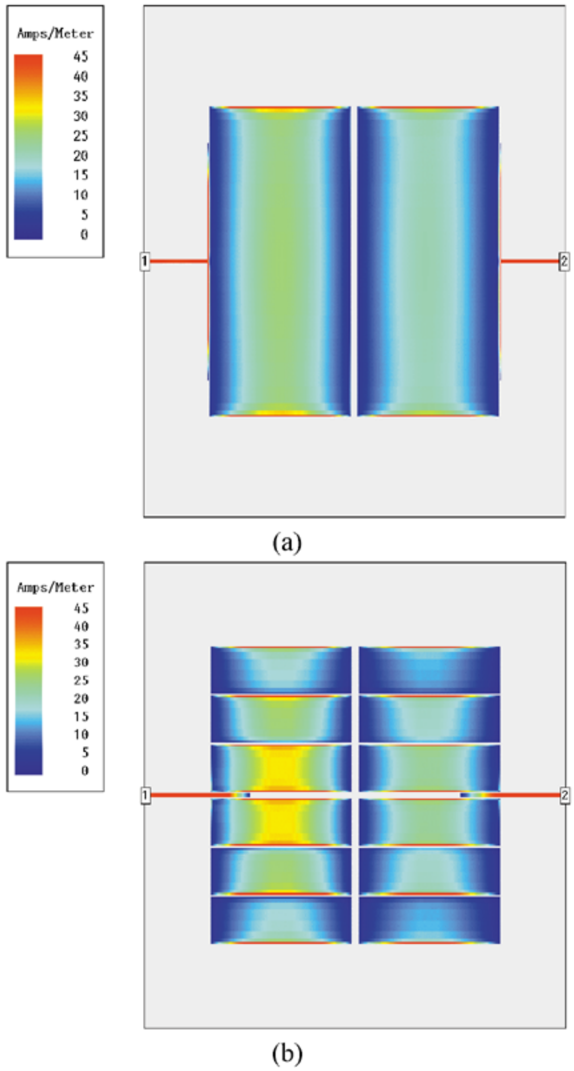


Fig. 8. Current density plots: (a) of the two-pole filter shown in Fig. 4(a) and (b) of the two-pole filter shown in Fig. 4(b).

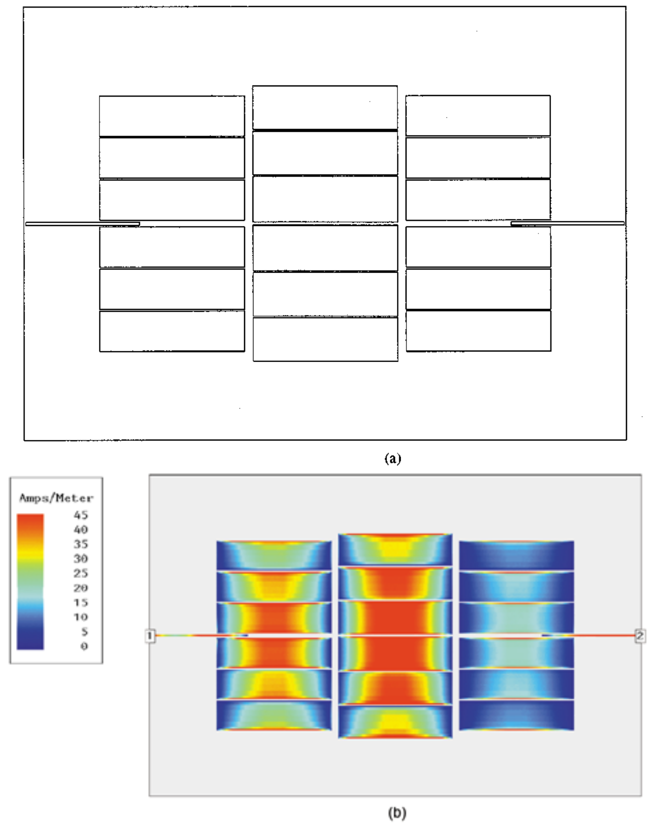


Fig. 9. (a) Layout and (b) current density plot of a three-pole filter using split resonator and inserted I/O coupling structure.

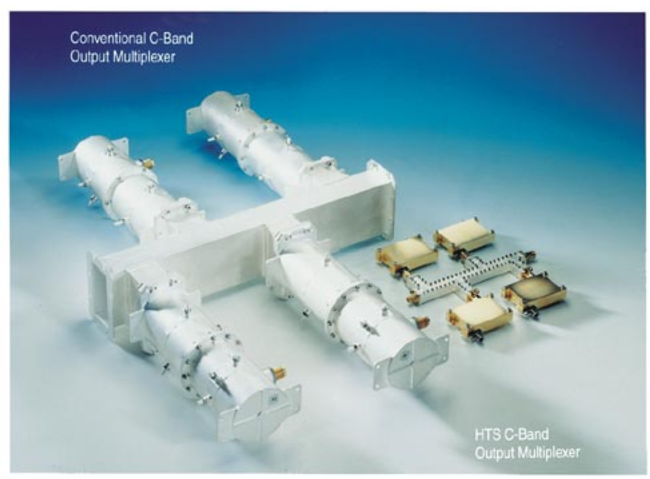


Fig. 10. Layout of a four-channel HTS output multiplexer employing planar HTS filters in comparison of a four-channel waveguide output multiplexer.

Fig. 10 illustrates the layout of a four-channel HTS output multiplexer in comparison with that of a four-channel conventional waveguide multiplexer. The measured RF performance of this HTS multiplexer is shown in Fig. 11. The planar HTS filters used in this multiplexer are five-pole 1% bandwidth having quasi-elliptic function. Fig. 12 illustrates the filter layout. Although this filter has a relatively large resonator size, it was capable of only handling 7 W when it was tested under high power in an LN2 Dewar. These filters were only used to demonstrate the feasibility of designing manifold-coupled multiplexers using planar HTS filters. With the use of the high-power planar split-resonator filters similar to that shown in Fig. 10, the power-handling capability can be extended to 30 W.

All the HTS films used to build the filters and multiplexers shown in Figs. 2, 8, 9, and 11 were supplied by DuPont, Wilmington, DE.

IV. Cooling Load of HTS Output Multiplexers

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 effective isotropic radiated power (EIRP) or reduction in the dc power required for the power amplifiers. However, the mass penalty of the cryocooler and associated electronic controller may overshadow any advantages gained with the use of HTS technology. In contrast to input multiplexers, superconductive output multiplexers typically have a considerably high heat load. Today's space-qualified cryocoolers that are capable of dealing with such heat loads are bulky and extremely heavy in mass. In this section, we present a detailed tradeoff analysis for

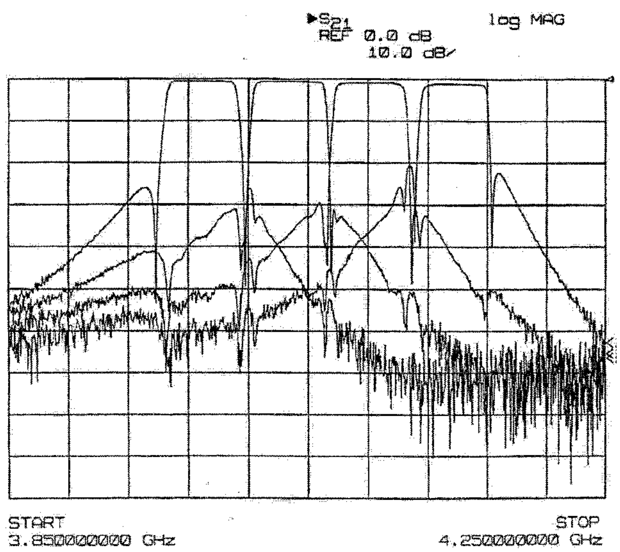


Fig. 11. Measured RF performance of the HTS multiplexer shown in Fig. 10.

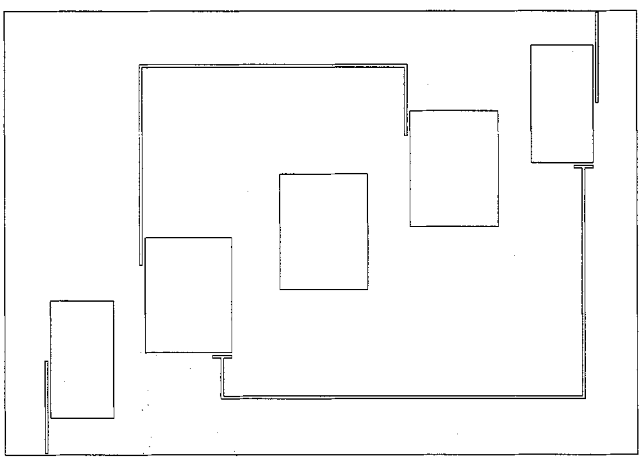


Fig. 12. Layout of the HTS filter used to build the four-channel multiplexer shown in Fig. 10.

output multiplexers. The objective is to highlight the issues that need to be addressed before output multiplexers are considered for space applications.

The cooling load of superconductive high-power multiplexers is mainly determined by the following:

1) heat dissipation inside the channel filters;
2) heat load of the I/O cables;
3) heat leaks through support structure and radiation.

The heat leaks through support structure and radiation through multilayer insulator (MLI) blanketing are typically small compared to the overall heat load. In this paper, we will focus on the heat load generated in the channel filters and I/O RF cables.

A. Heat Dissipation Inside the Channel Filters

In designing superconductive output multiplexers for satellite applications, the insertion loss of the HTS filter is a critical parameter. As the filter insertion loss increases, more power will be dissipated in the form of heat, which, in turn, could increase the cooling power demand to a level that is significantly high for current cooling technology. This concern is especially critical for multiplexers with a large number of channels.

There have been recently reports on the possibility of building HTS resonators with extremely high unloaded Q values in the range of 100 000's. Although such high Q values can be potentially achieved for single resonators, it is extremely difficult to achieve such high values for an integrated HTS filter that requires the use of tuning elements. The insertion loss of the filter is not only determined by the surface resistance of the HTS materials and the loss tangent of the dielectric substrate, but also by the package configuration and the type of tuning elements used.

The use of tuning elements is considered a must to meet the stringent performance typically required for output multiplexer applications. It should be mentioned that although waveguide technology has been known for more than two decades, tuning screws are still being used in designing waveguide multiplexers. Therefore, it is important that one takes into consideration the impact of the tuning screws in estimating the Q of the filter, which, in turn, would have a considerable impact on the heat dissipation.

Conventional waveguide output filters typically operate over a wide temperature range (-20 °C, 100 °C). The unloaded Q of the waveguide filter at 100 °C could degrade considerably. A typical C-band four-pole waveguide output filter with a 1% bandwidth can have an insertion loss as high as 0.25 dB at 100 °C. The HTS filters described in Section III exhibited an insertion loss of 0.125 dB, which corresponds to an unloaded Q of 15 000.

In the tradeoff analysis given in Section IV, we will consider Q values for HTS filters in the range of 15 000–100 000. The objective is to demonstrate that even if one achieves a Q of 100 000, there are still other issues that need to be addressed before using HTS filters for high-power applications. Namely, the availability of highly efficient cryocoolers as well as the availability of low-loss high-power thermally isolated RF transitions. These transitions are required to replace the traditional RF cables, which have a considerably high heat load.

B. Heat Dissipation of I/O Cables

For optimum use in HTS high-power applications, the RF I/O cables must satisfy the following three conditions.

1) The RF cables must have low insertion loss to reduce heat dissipation.
2) The RF cables must provide low conduction heat load.
3) The RF cables must be capable of handling high power.

It is difficult to find a commercially available RF cable that can reasonably meet the above three 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 insertion loss and may not be able to handle high RF power. A detailed analysis of heat load of coaxial RF cables is given in [13]. For a 4-GHz input power of 25 W, a 15-cm 0.085 stainless-steel cable would have a total heat load of approximately 1.3 W due to both heat dissipation and heat conduction. Such a heat load is considered high especially for

TABLE I
ASSUMPTIONS USED IN THE TRADEOFF ANALYSIS FOR HTS OUTPUT MULTIPLEXERS

PARAMTER	ASSUMPTION
Channel Filters	4-Pole, 1% bandwidth
Insertion Loss of Conventional filter + manifold (Lc)	0.25 dB
Achievable HTS filter insertion loss (Ls)	Calculated based on an achievable HTS filter Q of 15,000, 25,000, 50,000 and 100,000
Insertion loss of manifold and connectors in the HTS multiplexer (Lm)	0.03 dB
Attenuation of input/output thermally isolated RF transitions (Lt)	0.0, 0.002 and 0.005 dB/cm
Input RF power per channel for conventional technology (Pin)	10 – 50 Watts
Cryo-cooler efficiency	15:1
Efficiency of power amplifiers (η)	40 %

systems, which use a large number of I/O RF cables. It is evident that there is a need to develop thermally isolated low-loss RF transitions.

V. DC POWER REQUIREMENTS

The dc power required for the cryocooler is proportional to the cooling load, which the cryocooler has to handle. The typical cryocooler efficiency, for a cold temperature of 77 K and a rejection temperature of 300 K, is 15 : 1. This means that 15 W of dc power is required for each 1 W of cooling load. The cryocooler dc power could be offset by the potential saving in the dc power generated in the following two areas.

1) *Amplifier dc power*: The typical channel insertion loss (filter and manifold) of conventional C-band waveguide multiplexers is 0.25 dB. The use of HTS technology can potentially achieve a saving of 0.1–0.2 dB in the insertion loss (based on the achievable HTS filter Q). Such a saving in the insertion loss translates into less RF amplifier power, which, in turn, translates into less amplifier dc power.
2) *Heater dc power*: Conventional waveguide output multiplexers use heaters in order to minimize the frequency drift with temperature. The objective of these heaters is to ensure that the multiplexer temperature is within the designed temperature range in the case when some of the channels are in the backoff mode. A dc power of 2 W per channel is typically required for heaters on such systems. The use of HTS technology could eliminate the need to use these heaters, which represents another area of potential savings in mass and dc power.

VI. ISSUES FOR REALIZING HIGH-POWER HTS MULTIPLEXERS

In this section, we present a detailed analysis of mass penalty/saving and dc power requirement versus number of channels and RF input power. The analysis is based on the assumptions given in Table I. The reduction in amplifier dc power per channel (P_s) due to the improvement in filter insertion loss is given by

$$P_a = (1/\eta) \cdot P_{\text{in}} \cdot \left(1 - \left(10^{-(Lc-Ls-Lm-Lt)/10}\right)\right). \quad (1)$$

The dissipation per channel for the HTS technology is given by

$$\text{Heat dissipation/channel} = P_{\text{in}} \cdot 10^{-(Lc-Ls-Lm-Lt)/10} \cdot \left(1 - 10^{-(Ls+Lm+Lt)/10}\right) \quad (2)$$

where Lc, Ls, Lm, and Lt are defined in Table I.

In view of the assumptions given in Table I and with the use of (1) and (2), Table II provides the heat load versus achievable filter insertion loss and RF input power. All the numbers given in this table are for one channel. It should be also noted that Table II does not include the heat dissipation in the I/O thermally isolated RF transitions.

It can be seen from Table II that the potential saving in dc power disappears as the input RF power increases. For an input power of 50 W, the required cryocooler power exceeds the saving in amplifier and heater dc power even with the assumption of a zero heat load for the I/O RF transition and an achievable HTS filter Q of 100 000.

For reliability reasons, two cryocoolers and two electronic controllers are assumed, reflecting a conservative approach. The mass of the cryocooler is proportional to the cooling load, which the cryocooler needs to handle. Table III gives the mass of the state-of-the art space qualified cryocooler versus cooling power at 77 K [14].

Table IV illustrates the overall tradeoff analysis versus number of channels assuming an input RF power of 20 W and an achievable filter insertion loss of 0.038 dB (i.e., an achievable Q of 50 000). In order to demonstrate the significance of

TABLE II
REQUIRED CRYOCOOLER DC POWER FOR DIFFERENT VALUES OF HTS CHANNEL INSERTION LOSS ASSUMING THAT THE I/O RF TRANSITIONS HAVE A ZERO RF LOSS AND ZERO HEAT LOAD

Filter Insertion Loss	Heat dissipation per HTS channel	Cryo-cooler dc power per channel	Total reduction in dc power per channel, calculated using Eq (1) and by assuming a heater dc power of 2 watts/channel
Pin = 10 Watts			
0.125 dB (Q=15,000)	0.34 W	5.1 W	2.54 W
0.075 dB (Q=25,000)	0.23 W	3.45 W	2.82 W
0.038 dB (Q=50,000)	0.15 W	2.25 W	3.02 W
0.02 dB (Q=100,000)	0.11 W	1.65 W	3.12 W
Pin = 20 Watts			
0.125 dB (Q=15,000)	0.69 W	10.35 W	3.08 W
0.075 dB (Q=25,000)	0.46 W	6.9 W	3.64 W
0.038 dB (Q=50,000)	0.29 W	4.35 W	4.05 W
0.02 dB (Q=100,000)	0.22 W	3.33 W	4.25 W
Pin = 50 Watts			
0.125 dB (Q=15,000)	1.71 W	25.65 W	4.7 W
0.075 dB (Q=25,000)	1.15 W	17.25 W	6.1 W
0.038 dB (Q=50,000)	0.74 W	11.1 W	7.15 W
0.02 dB (Q=100,000)	0.55 W	8.25 W	7.62 W

TABLE III
MASS OF THE STATE-OF-THE-ART SPACE QUALIFIED CRYOCOOLER VERSUS COOLING POWER AT 77 K

Cryo-cooler Cooling Power at 77K	Mass of Space-qualified Cryo-cooler	Mass of Electronic Controller
Up to 4 Watts	1.25 kg	2 kg
Up to 10 Watts	5 kg	4 kg
Up to 30 Watts	12 kg	5 kg

TABLE IV
MASS AND HEAT LOAD OF HTS OUTPUT MULTIPLEXERS ASSUMING AN INPUT POWER OF 20 W AND A CHANNEL INSERTION LOSS OF 0.038 dB (i.e., AN ACHIEVABLE FILTER Q OF 50 000 AT C-BAND)

Number of Channels	Mass of Conventiona l Mux	Mass of HTS Mux including Packaging	Total Heat Load [Eq. (4)]	Mass of 2 Coolers & Electronics (Table III)	Mass Saving / Penalty [Eq. (3)]	DC Power Saving / Penalty [Eq. (5)]
Case I: RF Transition Thermal Conductivity = 0.0 watt. cm, attenuation = 0.0 dB/cm						
6	4.5 kg	0.96 kg	1.74 W	6.5 kg	(2.96) kg	(1.8) W
24	18 kg	3.84 kg	6.96 W	16 kg	(1.84) kg	(7.2) W
40	30 kg	6.40 kg	11.6 W	34 kg	(10.4) kg	(12) W
80	60 kg	12.8 kg	23.2 W	34 kg	13.2 kg	(24) W
Case II: RF Transition Thermal Conductivity = 1.7 watt. cm, attenuation = 0.005 dB/cm, input /output cable lengths = 5 cm each						
6	4.5 kg	0.96 kg	6.5 W	16 kg	(12.4) kg	(74) W
24	18 kg	3.84 kg	26.1 W	34 kg	(19.8) kg	(299) W
40	30 kg	6.40 kg	43.5 W	-	-	(499) W
80	60 kg	12.8 kg	87.0 W	-	-	(998) W
Case III: RF Transition Thermal Conductivity = 0.6 watt. cm, attenuation = 0.002 dB/cm, input /output cable lengths = 5 cm each						
6	4.5 kg	0.96 kg	3.75 W	6.5 kg	(2.96) kg	(33) W
24	18 kg	3.84 kg	15.0 W	34 kg	(19.8) kg	(133) W
40	30 kg	6.40 kg	25.0 W	34 kg	(10.4) kg	(221) W
80	60 kg	12.8 kg	50.0 W	-	-	(443) W

the heat load problem of the I/O cables, we consider in Table IV the following three cases.

Case I

A hypothetical case, where the RF cables were assumed to have negligible heats load, i.e., the heat load is only due to dissipation in the RF channels.

Case II

Assume that the I/O cables are 5-cm-long 0.141–diameter stainless-steel cables with a thermal conductivity of 1.7 W · cm and an attenuation of 0.005 dB/cm at 77 K.

Case III

Assume the availability of I/O RF transitions with a heat load of 60 mW and an attenuation of 0.02 dB (i.e., an effective thermal conductivity of 0.6 W · cm and an effective attenuation of 0.002 dB/cm). To our knowledge, no such RF transitions exist commercially at the present time. The total mass saving, total heat load, and dc power savings shown in Table IV are calculated as follows:

$$\begin{aligned}\text{Mass saving} &= \text{Mass of Waveguide Mux}\\ &\quad - \text{Mass of HTS Mux}\\ &\quad - \text{Mass of two (coolers + elect.)} \quad (3)\\ \text{Total heat load} &= \text{Heat dissipation in HTS filter}\\ &\quad + \text{Heat load of RF I/O cables} \quad (4)\\ \text{Total dc power saving} &= \text{Saving in amplifier dc}\\ &\quad + \text{power Saving in heater dc power}\\ &\quad - \text{Cryocooler dc power.} \quad (5)\end{aligned}$$

The data given in Table IV indicates that, for a 24-channel multiplexer, the use of 0.141 SS cables as an I/O RF transition (i.e., Case II) can translate to a dc power penalty of 299 W. It can be also observed that the use of HTS technology will translate to a mass penalty for the 24-channel output multiplexer even if one assumes that the filters have unloaded Q of 50 000 and that the cables have zero heat load (i.e., Case I). For a large number of RF channels, one may be able to achieve mass saving. However, even with the assumption of the availability of low-loss thermally isolated transitions (i.e., Case III), the use of HTS technology for 20 W/channel systems will lead to a dc power penalty rather than a dc power saving.

VII. Conclusions

This paper has demonstrated the feasibility of designing a high-temperature superconductive manifold-coupled contiguous-type multiplexer that is capable of handling the power requirements of conventional C-band satellite systems. This paper has also presented a novel configuration for an HTS planar filter that is capable of handling extremely high power levels. Despite the tuning complexity of planar thin-film filters, this paper has demonstrated the successful integration of planar HTS thin-film filters on a coaxial manifold to build output multiplexers.

A detailed tradeoff analysis has been presented on the use of HTS technology for high-power multiplexers for C-band satellite systems. It is concluded that in view of the current cryocooler technology and spacecraft ambient environment for electronic hardware, the only clear advantage of using the HTS technology for a typical high-power multiplexer (50–200 W 24–36 channels) is size reduction. However, the size reduction advantage may be overshadowed by the mass and dc power penalties associated with the use of the cryocooler.

For systems that have large number of channels and operate at relatively low RF power (i.e., 5–10 W with more than 80 channels), in addition to size reduction, the use of HTS technology can also lead to mass reduction. However, in order to achieve these advantages, there is a need to develop low-loss thermally isolated RF transitions. The development of such transitions is as important as the development of high-Q HTS filters. The key issue, however, for successful implementation of HTS output multiplexers for commercial applications is the development of a highly efficient cryogenic environment in the spacecraft.

The tradeoffs given in this paper for the use of high-power HTS equipment assume current spacecraft configuration and the available HTS materials. Any reduction in the temperature environment for HTS equipment via passive cooling or other means can provide a large reduction in mass and power required for active cryocoolers. The same advantage will result if new HTS materials can be found with higher T_c. Assuming such advances can provide an acceptable tradeoff for the required cryogenics, one can conceive of HTS-based communications payloads, including low-power receive sections as well as high-power output circuits. At lower frequencies, such as C-band satellite systems, HTS could provide large savings in the mass and volume of payload equipment. At higher frequencies, the performance advantages can be enormous. For Ka-band satellites, the use of HTS technology could provide a 1 dB higher EIRP and a 2-dB improvement in G/T. Such an advantage would have a significant impact on the commercial viability of higher frequency satellites.

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