Low Loss Multiplexers with Planar Dual Mode HTS Resonators

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(Invited Paper)

***Abstract*— High temperature superconductivity space experiments (HTSSE-I and II) are aimed to demonstrate the feasibility of using high temperature superconductivity (HTS) technology in space systems. In communication satellites, high performance filters and multiplexers represent key microwave components of the payload. Utilization of HTS films in these devices is presented in this paper. The basic HTS resonator/filter structures (including HTSSE-I resonator/filter) suitable for these applications are described. The multiplexer designs and measured results are also described (including the HTSSE-II multiplexer).**

I. Introduction

COMMERCIAL satellite communication systems continue to provide significant challenges to microwave designers. Many technological advances are required to reduce mass and volume of the satellite payload, and at the same time increasingly stable components are needed coupled with more efficient delivery of higher effective isotropic radiated power (EIRP). In these communication systems, the available (allocated) frequency spectrum is a primary consideration. Due to the nonlinear nature of the available power amplifiers (SSPA's or TWTA's), the channelization of the allocated frequency band into a number of channels (so called transponders) is necessary. The typical communication payload usually contains a receive antenna, wide band filters, receivers (which include very stable local oscillators), input multiplexers, a switching network, high power amplifiers, output multiplexers, and a transmitting antenna (also known as a bent pipe transponder). A simplified block diagram of the transponder is shown in Fig. 1. Antennas, receivers, switching network, and high power amplifiers are more easily designed to be wide band, and therefore have minimal impact on the amplitude and phase of the transponder channel. However, individual filters in filter banks (multiplexers) are relatively narrowband (1–3%) and this drives the overall transmission performance, both in amplitude and phase (group delay). As a consequence, these filters are governing the characteristics of the communication transponder and their design is extremely important [1]–[3]. For this reason, the multiplexers are typically the focus of the design of the satellite transponder, and a significant effort is generally made to optimize their characteristics. At the same time, minimum mass and volume is needed.

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II. Suitability of HTS Resonators for Satellite Filters

In communication satellite applications, filters and multiplexers impose severe constraints as far as the weight and volume of a communication transponder is concerned. Traditionally, to reduce weight, three implementations of cavity filters are used: thin-wall INVAR, GFRP (graphite fiber reinforced plastic), and dielectric resonator technologies. A dual mode approach pioneered by Atia and Williams [4] (using degenerate cavity modes) can be used to realize conveniently high performance elliptic function filters requiring coupling between nonadjacent cavities. However, even such advanced filters present a major constraint in satellite layout and further reduction in size and weight was necessary.

A. Basic Resonator/Filter Structures

In the past, a number of different filter configurations based on high dielectric constant, low loss ceramics have been developed [1]. These techniques involved suspending a cylindrical resonator inside a waveguide cavity below cutoff. In some cases, for further reductions in size, the use of so-called "post" resonators [5], or half-cut (quarter-cut) image dielectric resonators with partial conductive walls was proposed. Typical modes of these structures and their field distributions are shown in Fig. 2. Using newly developed high temperature superconductors (HTS) practically eliminates conductive losses (which were a significant drawback of these resonators), and the excellent dielectric properties (Q factor) of the typical structures are retained. A great deal of research into HTS fabrication has been applied in the attempt to find suitable substrate materials and to develop reliable methods of thin film deposition. Recent developments have produced good films, typically on Lanthanum Aluminate or related compounds. However, these substrate materials seriously degrade device performance due to their relatively high loss tangent. Recently, ceramics from a number of companies have shown exceedingly high Q factor at low temperatures. Kobayashi [6] has reported that this type of ceramic can achieve Q factors of over 140 000 at 77 K. Even better Q factors (more than several millions) can be achieved by

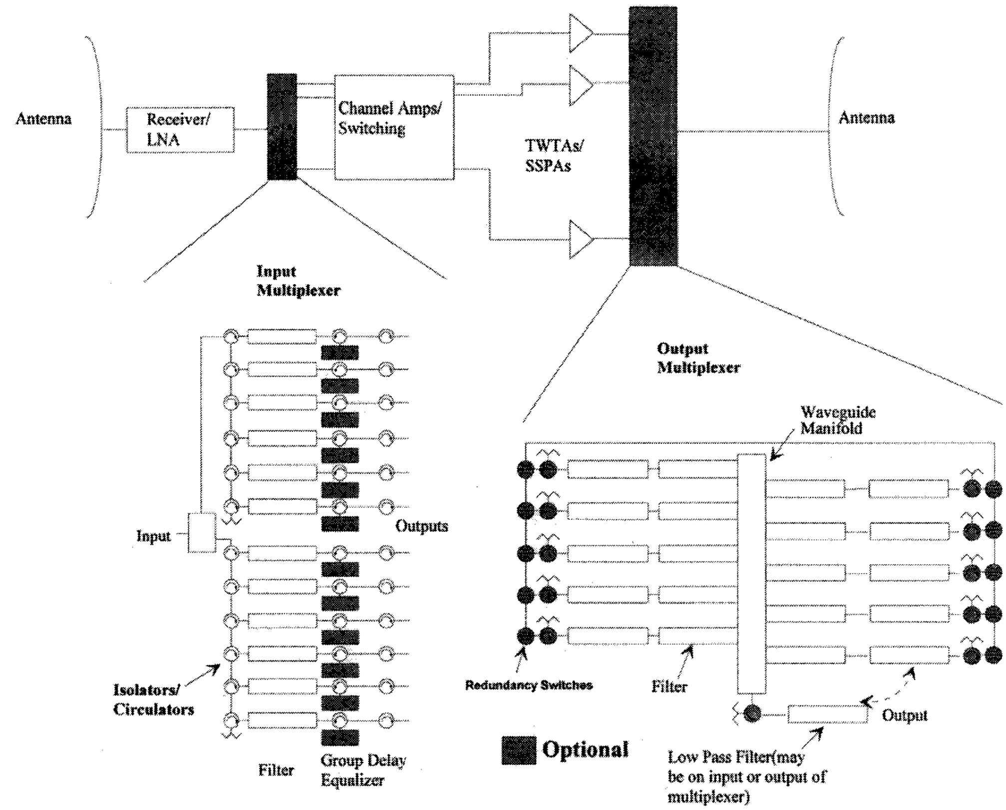


Fig. 1. Simplified block diagram of a communication satellite payload, illustrating the function of the input and output multiplexers (filter banks).

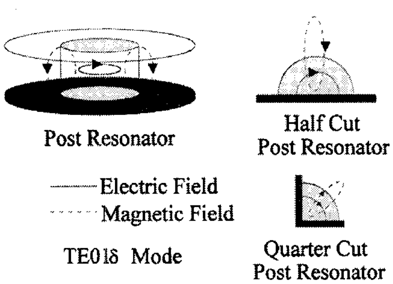


Fig. 2. Illustration of post dielectric resonator and their corresponding electromagnetic field configurations.

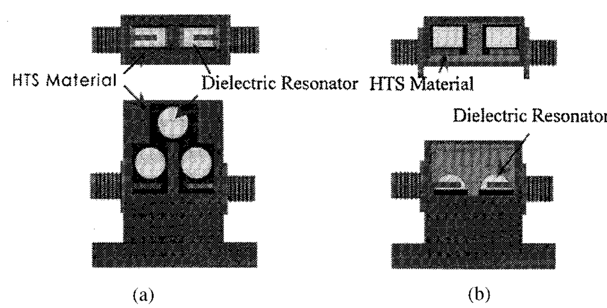


Fig. 3. Sketches of single mode, dielectric/HTS resonator filters including: (a) post resonator and (b) half-cut resonator.

using sapphire monocrystals as a dielectric [7], [8]. Virtually eliminating dielectric losses leaves only dissipation due to the finite conductivity of the cavity walls. Further enhancement is made by either enlarging the cavity (limited by waveguide moding) or replacing the metal walls with HTS material. HTS walls are particularly attractive since they can be placed directly in contact with the dielectric with little degradation of performance, producing a very miniature, extremely high Q resonator. Since HTS thin films have been primarily deposited on flat substrates, the realized filters use HTS on the ends of the resonators only. Fig. 3(a) shows the configuration of a three-pole hybrid dielectric resonator post filter using a high temperature superconductor. The Q factor expected for this filter, using a high quality thin film, is over 50 000 at 77 K, therefore reflection losses are dominant. Fig. 3(b) shows a half-cut dielectric resonator filter. This design has the advantage of requiring only one side to be coated with HTS material, reducing size and cost at the expense of a lowered Q factor. A further extension of this idea is to cut the resonator down to quarter size, offering the minimum volume, but with two sides of HTS and a reduced Q factor. An advantage of the quarter-cut design is the effective elimination of spurious modes. Any of these designs may be easily extended to include nonadjacent resonator couplings through simple mechanical means and are thus suitable for steep satellite channel filters [9].

A number of dielectric resonator filters were fabricated including filters for the Naval Research Laboratory High Temperature Superconductivity Space Experiment (HTSSE-I). A three-pole Chebyshev design was chosen for a single mode post design. Testing took place by initially using substitute copper substrates to rough tune the filter and to size the

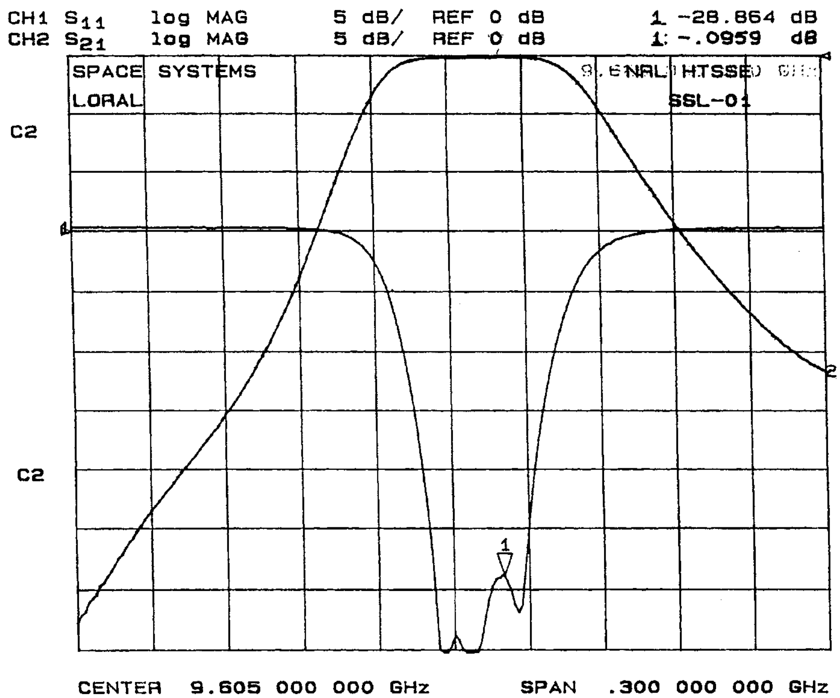


Fig. 4. Measured insertion loss and return loss performance of a three-pole, single mode dielectric/HTS resonator filter developed for HTSSE-I.

resonators. Final tuning involved installing the HTS substrates and tuning the filter while cooled with liquid nitrogen. This technique resulted in an excellent, well tuned filter. Fig. 4 shows the passband performance of the single mode dielectric resonator/HTS filter. A two-pole half-cut resonator design also demonstrated excellent performance.

The dielectric resonator/HTS combination offers a variety of advantages for use in narrowband filter applications, where high Q factor and precise alignment are required. They are also relatively small size and low cost while exhibiting exceptionally high performance.

Planar design techniques for single mode microstrip filters such as broad side edge-coupled filters have long been established [10], [11]. However, these filters are of limited utility for most high performance microwave applications due to their typically high insertion loss and impracticality for filter passbands of less than 5%. The high performance requirements for communication satellite frequency multiplexers typically require the use of dual mode cavity or dielectric resonator filters to realize self-equalized, quasielliptic responses having pass bands often less than 1%. Cavity and dielectric resonator filters have the drawbacks of relatively large size and high cost.

Fig. 5 illustrates three dual mode microstrip resonator structures that are the building blocks of dual mode planar filters. In each of these structures, a perturbation has been added to a previously single mode resonator at a point that is 45° from the axes of coupling to the resonator. The perturbation in the symmetry of the resonator at the 45° offset location facilitates coupling between two orthogonal modes within the resonator. The axes of coupling to the resonator are orthogonal, so each couples energy independently to and from only one of the orthogonal modes within the resonator, as is required to realize dual mode filters of more than two poles. The perturbations can take on any number of forms, and the extent to which they disturb the resonant fields, determines the coupling coefficient between the two orthogonal modes. The perturbations shown in Fig. 5 were chosen because of their repeatability, symmetry, and tunability.

The square resonator of Fig. 5 is an adaptation of a single mode resonator commonly used for microstrip "patch" antennas [12]–[14] and was previously used as a discriminator. The circular resonator is an adaptation of a single mode disk resonator that is also used in microstrip antennas and has been used previously to realize single mode microstrip filters. The dual mode ring resonator is an adaptation of the single mode resonator commonly used for a variety of purposes including microstrip transmission line evaluation. Perturbations in ring resonators have been used previously to excite degenerate modes [15], [16]. The resonators described can be arranged in a number of ways to realize dual mode microstrip filters. The sketch in Fig. 6 illustrates a dual mode, four-pole Chebyshev filter realized using two square patch resonators. The coupling of the dual orthogonal modes is facilitated by the asymmetric "cut away" corner geometry. Capacitive coupling to and from the filter is achieved by the microstrip gaps. One of the principle advantages of this new class of planar filters over other classes of microstrip filters is that it facilitates the practical realization of elliptic and quasielliptic function responses. The required cross coupling is implemented using short sections of microstrip.

These resonators can also be arranged in a stacked configuration, where coupling between the dual mode resonators is

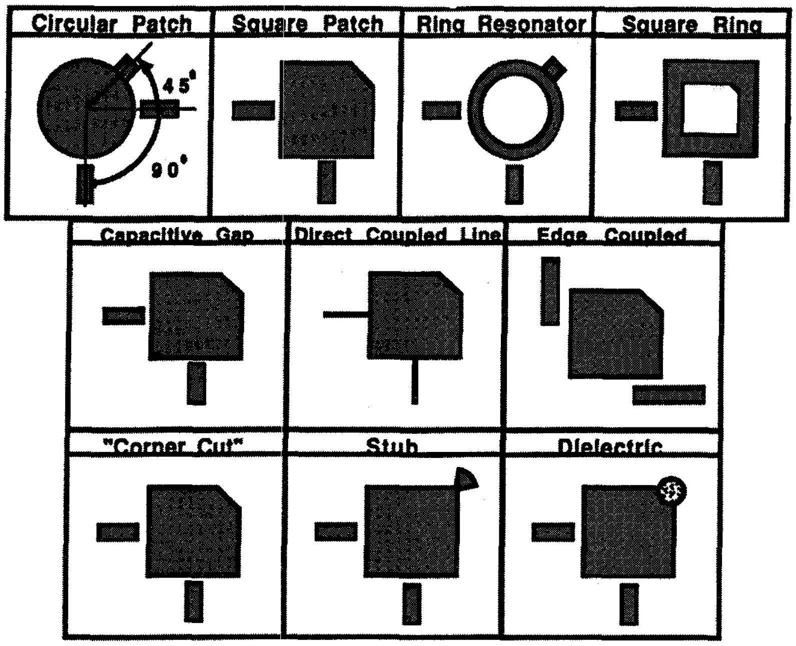


Fig. 5. Building blocks of dual mode planar HTS filters. The top row illustrates the resonator structures, the middle row illustrates coupling to the resonators, and the bottom row illustrates possible perturbations to the resonators to accomplish coupling between the dual orthogonal modes.

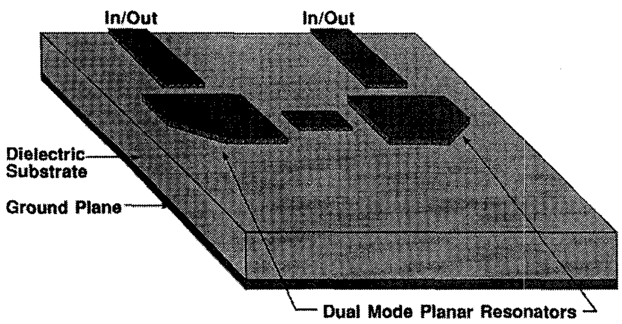


Fig. 6. Illustration of a four-pole, dual mode Chebychev filter in a microstrip configuration.

controlled through coupling apertures or irises similar to those used for the realization of cavity and dielectric resonator filters. Similar coupling apertures are also used in planar antennas [17], [18]. This stacked (or multilayer) filter configuration has advantages over the previously introduced dual mode planar filters in that it is somewhat smaller and lighter, but more importantly, it offers the potential for tunability through the selection of iris and resonator dimensions during the testing stages of development. This configuration can be used to realize any of the filter types that are currently implemented using dual mode cavities or dielectric resonators including elliptic function and/or self-equalized responses. The stacked planar structure offers dramatic reductions in size, mass, and potentially, cost as compared to the currently used cavity designs. This new class of filters is ideally suited for fabrication using thin film, high temperature superconductors for high Q performance. The stacked planar filters described in this work can be based on a variety of dual mode, planar resonator structures similar to those used in dual mode microstrip filters. These include square patches, circular disks, and rings. Basic field configurations for these resonators in single mode form can be found in [12]. In the filter configurations, the dual mode stripline resonators are stacked as shown in Fig. 7. Coupling energy between the resonators is implemented by including a coupling aperture or iris in the ground plane shared by the two resonators. This concept can obviously be extended to realize filters of any number of poles. For the case of the slot apertures, the coupling between each pair of modes can be controlled independently by varying the length of the slots. The size and mass of the filters based on this multi-layer concept is extremely small in comparison to cavity and dielectric resonator designs and is also significantly smaller than that required for the previous dual mode microstrip designs. Each dual mode resonator is approximately one half wavelength (at Fc) long and each resonator requires the thickness of 2 substrates. Assuming a substrate thickness of 0.020″, each dual mode resonator requires a thickness of only 0.040″. A similar multi-layer design can be applied to microstrip filters. An important aspect of the multi-layered filters is tunability. For these filters, tuning can be achieved by a combination of select-at-test substrates containing resonators or irises of varying dimensions, and the introduction of tuning screws which perturb the field configurations of the resonant modes.

B. Modeling

To utilize a resonator in filter designs, one needs to characterize the self-resonating frequency of the resonator, as well as the inter-coupling between resonators. In case of a

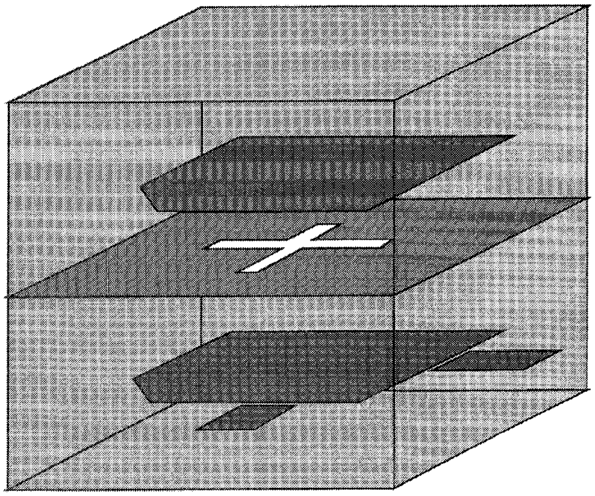


Fig. 7. Illustration of a four-pole dual mode planar filter in a stacked configuration. This filter is made from two dual mode stripline resonators that are vertically stacked and coupled together through an iris in their common ground plane.

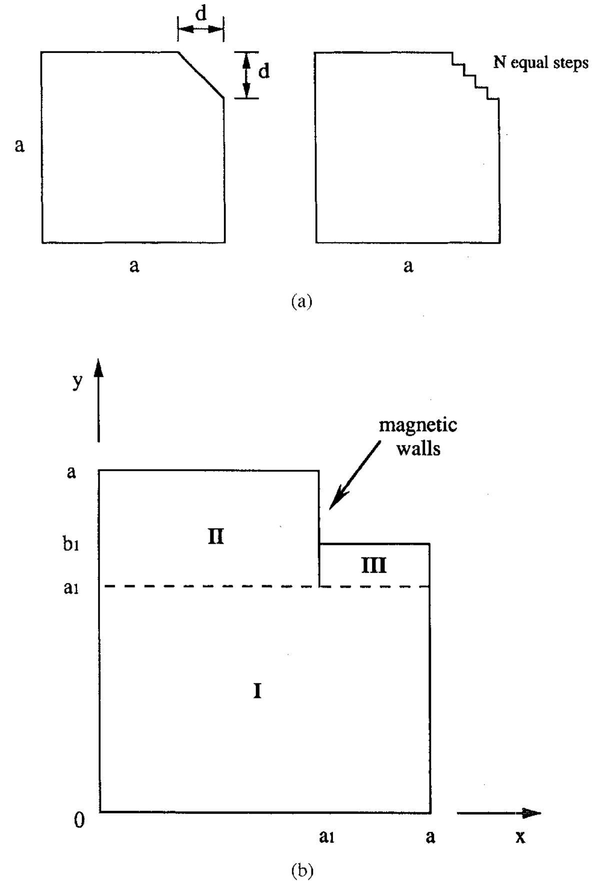


Fig. 8. Modeling of dual mode planar filters is illustrated. (a) Cut away corner section is modeled as a series of N steps. (b) N = 1 step.

dual mode resonator, inter-coupling between the orthogonal modes has to be accurately evaluated. There are a number of modeling techniques commonly used on the field studies of planar resonators [12], [13], [19]. This paragraph outlines a simplified mode-matching method to calculate the coupling coefficient of the orthogonal modes. A corner-cut microstrip square resonator is used as an example.

The 45°-cut of the square resonator is first replaced by N number of equally-spaced steps as shown in Fig. 8(a). Apparently, the two diagrams in Fig. 8(a) are identical as N approaches infinity. In practice, N converges rapidly for $N \geq 5$ depends on the d/a ratio. Smaller d/a (i.e., filter with narrower bandwidth) requires fewer number of steps. Furthermore, each discontinuity is partitioned into three distinct regions. Fig. 8(b) shows a $N = 1$ planar waveguide model in which an incoming wave from region I entering the discontinuity at $y = a_1$ can be scattered into regions II and III as well as reflected back into region I. After imposing the magnetic walls at the boundary and setting $b_1 = a_1$, the square resonator cavity is recovered.

Within the cavity model of microstrip resonator, the electric field E has only the z-component; both E and H fields are independent of z-coordinate; and no tangential component of H exist on the magnetic walls. The modal functions for the model shown in Fig. 8(b) are

$$\begin{aligned}\Psi_{1m} &= \cos(\beta_{1m}x)\cosh(\gamma_{1m}y)\\ \Psi_{2p} &= \cos(\beta_{2p}x)\cosh[\gamma_{2p}(a-y)]\\ \Psi_{3q} &= \cos(\beta_{3q}x - a_1)\cosh[\gamma_{3q}(b_1-y)]\end{aligned}$$

where Ψ_{ij} is the jth modal function in the ith region, $\beta_{1m} = m\pi/a$, $\beta_{2p} = p\pi/a_1$, $\beta_{3q} = q\pi/a - a_1$, and $m, p, q = 0, 1, 2, 3 \cdots$ all integers, $\gamma_{ij} = \sqrt{\beta_{ij}^2 - k_j^2}$ is the complex propagation constant of the jth mode in the ith region, $k_j^2 = (\omega/c)^2\varepsilon_r$ is the resonant wavenumber square of the jth mode, and ε_r is the effective dielectric constant of the substrate. The corresponding electromagnetic fields in the ith region are given by

$$\begin{aligned}\vec{E}_i &= E_i\hat{z}\\ &= \sum_m A_{im}\Psi_{im}\hat{z}\end{aligned}$$

and

$$j\omega\mu\vec{H}_i = \hat{z} \times \nabla_t E_i.$$

Applying the continuity conditions at the junction and the orthogonality relations on the sinusoidal functions, a set of equations is obtained and grouped into a matrix form. The infinite number of allowed modes are now truncated to reduce the number of equations to a manageable size i.e., $m = 0, 1, 2 \cdots, (M-1)$, $p = 0, 1, 2, \cdots, (P-1)$, and $q = 0, 1, 2, \cdots, (Q-1)$, where M, P, and Q are the total number of eigen-modes chosen for region I, II, and III, respectively. To further simplify the calculation [19], M, P, and Q are chosen such that $M = P + Q$, and $P/M = a_1/a$.

Now the problem is reduced to calculate the resonant wavenumber k_j such that the determinant $|D| = 0$, where D is a $M \times M$ matrix with elements

$$D_{pm} = H_{mp}[\gamma_{2p}\tanh(\gamma_{2p}\delta) + \gamma_{1m}\tanh(\gamma_{1m}a_1)]$$

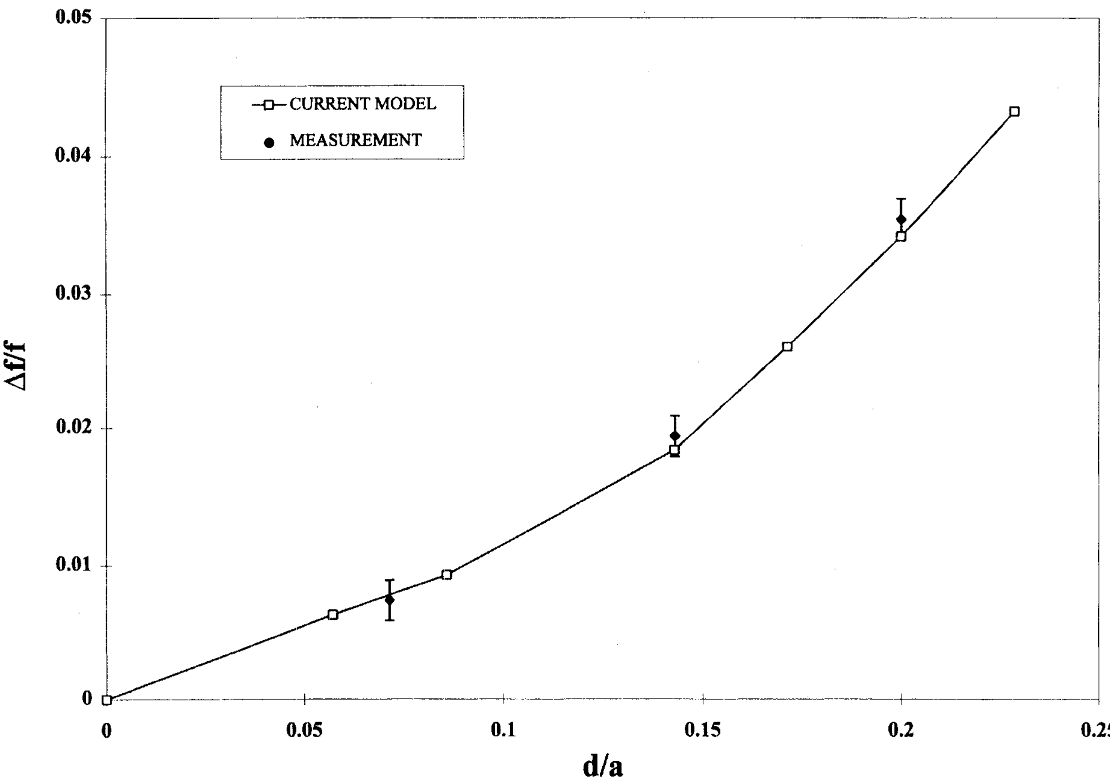


Fig. 9. Comparison of calculated and measured results for the modeling approach presented herein for dual mode planar resonators.

for $0 \leq p < P$, and

$$D_{qm} = \overline{H}_{mq}\gamma_{1m} \sinh(\gamma_{1m}a_1)$$

for $P \leq q < M$, where δ is the step width = $(a_1 - a)$,

$$H_{mp} = \frac{1}{C_m}\int_0^{a_1} \cos(\beta_{1m}x)\cos(\beta_{2p}x)\,dx,$$

$$\overline{H}_{mq} = \frac{1}{C_m}\int_{a_1}^{a} \cos(\beta_{1m}x)\cos[\beta_{3q}(x-a_1)]\,dx$$

and C_m are the corresponding normalization constants.

The above procedure is generalized to N number of steps. The calculated k_j's are then converted into the frequency splitting of the fundamental orthogonal modes Δf. Results of the calculations, and the comparison with measurements of 0.025″ thick alumina square patches at C-Band frequencies are plotted in Fig. 9. The coupling coefficient, which is directly proportional to $\Delta f/f$, is then extracted for bandpass filter design.

III. HTSSE-II Planar Dual Mode HTS Filters

A. Filter Design

For the second High Temperature Superconductivity Space Experiment (HTSSE-II) we demonstrated a 4-channel satellite input multiplexer based on dual mode planar HTS filters. These filters are built from a variation of the dual mode resonator building blocks illustrated in Fig. 5. One of the HTSSE-II filters is shown in the photograph of Fig. 10.

The HTSSE-II filters are based on a four pole, elliptic function design. The dual mode resonators are realized in a suspended substrate configuration by suspending a square Thallium HTS film within a waveguide cavity below cutoff. Energy is coupled into the filter by means of coaxial coupling probes which extend into the cavities. Coupling between the dual orthogonal modes supported by each individual resonator is accomplished by introducing a tuning screw near the corner of the resonator. This screw perturbs the electromagnetic fields supported by the resonator in a way similar to the cut away corner geometry illustrated in the microstrip filter illustrated in Fig. 5. The perturbation results in a reactive coupling between the two orthogonal modes supported by each individual resonator. The coupling value is controlled by varying the depth of the screw into the cavity. Primary coupling between the resonators is controlled by introducing a screw which closes off part of the slot between the cavities. Coupling between nonadjacent modes is accomplished by passing a coaxial probe between the cavities. The nonadjacent coupling is required to realize the desired elliptic function response.

The primary advantage of the suspended substrate configuration for the dual mode planar resonators is ease of tunability as compared to the microstrip or stripline configurations. In the suspended substrate geometry, the electromagnetic fields are not confined to the substrate as they tend to be in the microstrip and stripline configurations. This facilitates tuning of the resonators using conventional tuning screws and coupling to the resonators through conventional structures such as irises

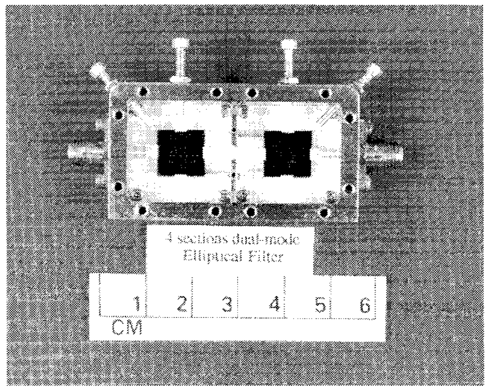


Fig. 10. Photograph of a dual mode suspended substrate HTS filter. Four of these filters were integrated to a multiplexer for the HTSSE-II.

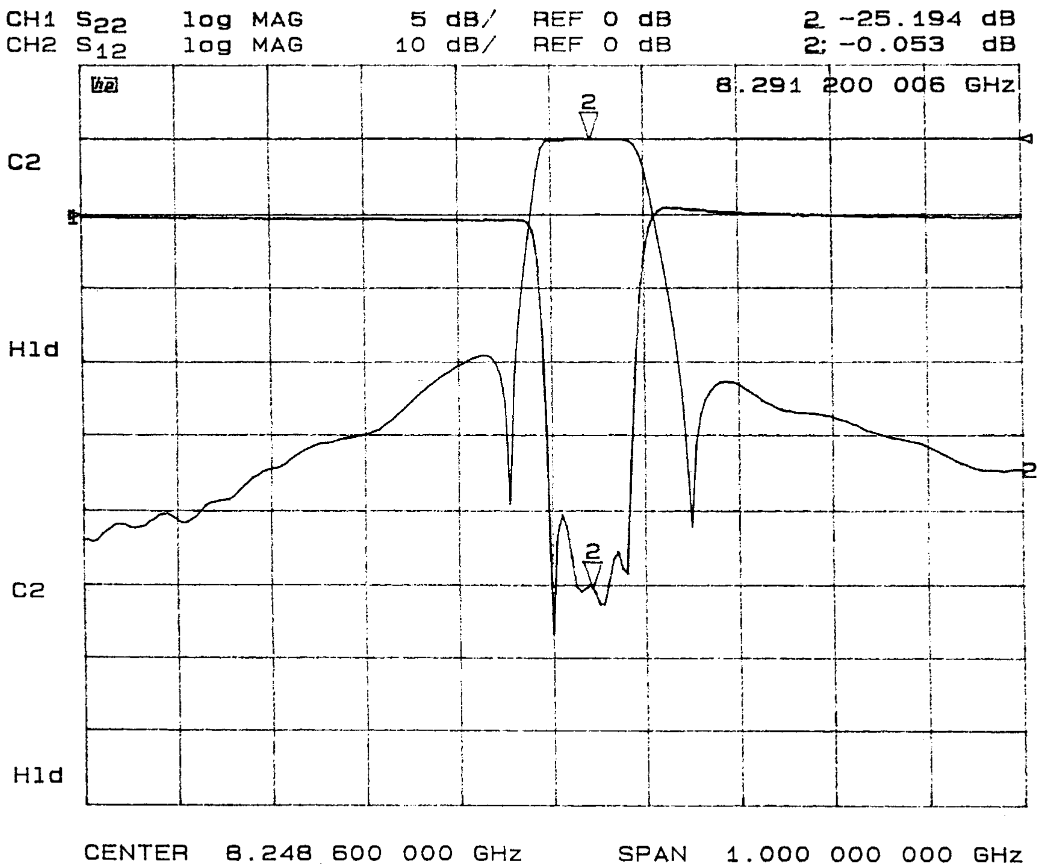


Fig. 11. Measured rejection and return loss performance of the HTSSE-II filter illustrated in Fig. 10.

and probes. For the HTSSE-II filters, tunability proved to be a great advantage as the filters could be tuned to any center frequency within a 50 MHz band and the bandwidth could be varied by tens of MHz. It also allowed for precise selection of bandwidth and center frequency within the band as is required for satellite applications.

B. Measured Results for HTSSE-II Filters

Several dual mode suspended substrate filters were built and tested to determine their electrical performance characteristics. In general, the performance was excellent. Fig. 11 shows the measured rejection and return loss performance of a typical filter prior to integration into a multiplexer. The filter has 20 dB return loss and approximately 0.05 dB insertion loss. The measurement was taken at approximately 80 K. Each of HTSSE-II filters was tuned for optimum performance at 80 K using special tooling.

IV. HTSSE-II MULTIPLEXER

A. Multiplexer Design Considerations

The planar superconducting filters offer an outstanding size reduction when taken alone. However, for most typical communications applications, a set of filters must be multiplexed

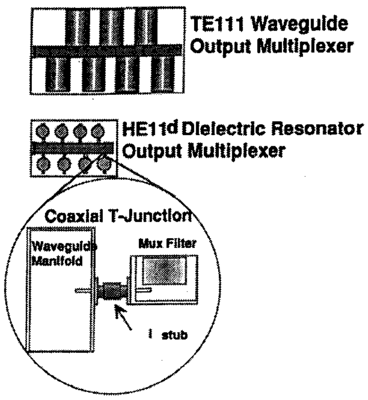
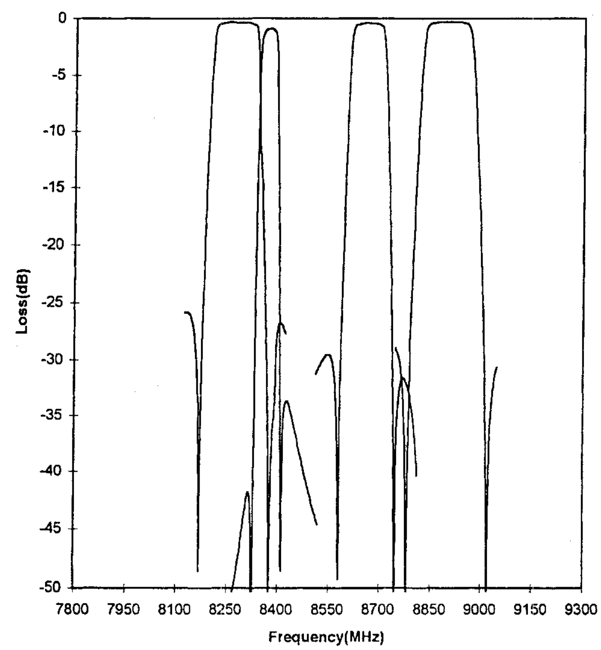


Fig. 12. Illustration of a conventional dielectric resonator multiplexer in comparison to a multiplexer based on cavity filters. The waveguide/coaxial/filter connection concept illustrated here is employed on the HTS multiplexer built for HTSSE-II.



M ELEMENT MATRIX
0.0000 0.9395 0.0000 -0.1984
0.9395 0.0000 0.8133 0.0000
0.0000 0.8133 0.0000 0.9395
-0.1984 0.0000 0.9395 0.0000

INPUT TRANSFORMER= 1.1970
OUTPUT TRANSFORMER= 1.1970

Fig. 13. Coupling matrix used in the design and optimization of the four-pole HTSSE-II filters.

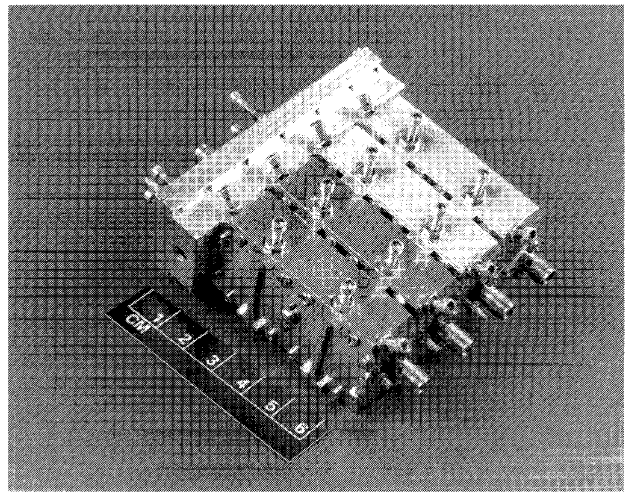


Fig. 14. Photograph of the waveguide/probe coupled HTSSE-II multiplexer based on dual mode, suspended substrate HTS filters.

in order to provide a combining or splitting function. Typical techniques include hybrids-splitters, circulator dropping networks, and direct combination. Splitters or hybrids offer the advantage of simple design and excellent symmetry, at the expense of greatly increased insertion loss. For systems which need low loss to improve noise figure, or have a significant RF power requirements, this type of combining is clearly inadequate. Circulator networks have been used for many years in low power, channelizing functions for satellite input multiplexers due to their inherent isolation of multiple channels (assuming adequate guard-band between channel edges) and relatively low loss compared to a hybrid design. However, this does mean that every channel must include at least one extra circulator, increasing size, weight, insertion loss, and cost. The circulators may well be much larger and heavier than the HTS filter itself! Direct combination using a RF component such as a waveguide or coaxial T-junction offers that advantages of potentially minimal weight increase, low loss, and low cost. Some added difficulty may be expected in this approach due to the need to tune all channels simultaneously, although this is done routinely in satellite output multiplexer applications.

For the HTSSE-II multiplexer, a direct combination method was chosen. Several types of combiners were available, including coaxial/coaxial and coaxial/waveguide. In prior years, we developed an output multiplexer using dielectrically loaded filters which employed a coaxial/waveguide T-junction with excellent success [3]. This multiplexer consisted of eight-channels, each having a coaxial probe into a WR229 waveguide section. The spacings of filters, the length of each probe into the waveguide, as well as the stub length between the waveguide and the filters were adjusted and optimized for best performance. Fig. 12 shows the multiplexer configuration and size as compared to a conventional cavity multiplexer. Details of the waveguide/coax/filter connection is also revealed.

Since this design had been well reproduced in earlier work, a coaxial/waveguide junction was also chosen for the HTSSE-II multiplexer. Although waveguide is often seen as large and bulky, in this application the waveguide manifold proved to be relatively compact and short. One design consideration with the HTSSE-II mux was the need to conform to size requirements of the HTSSE-II package, which did not allow for truly optimal spacing of the filters. In future designs, an all coaxial or stripline combiner (probably superconductive) could be used so the filter spacing could be arbitrarily chosen. Since the output was not intended to be waveguide, each side of the manifold was shorted, and a coaxial probe placed in the

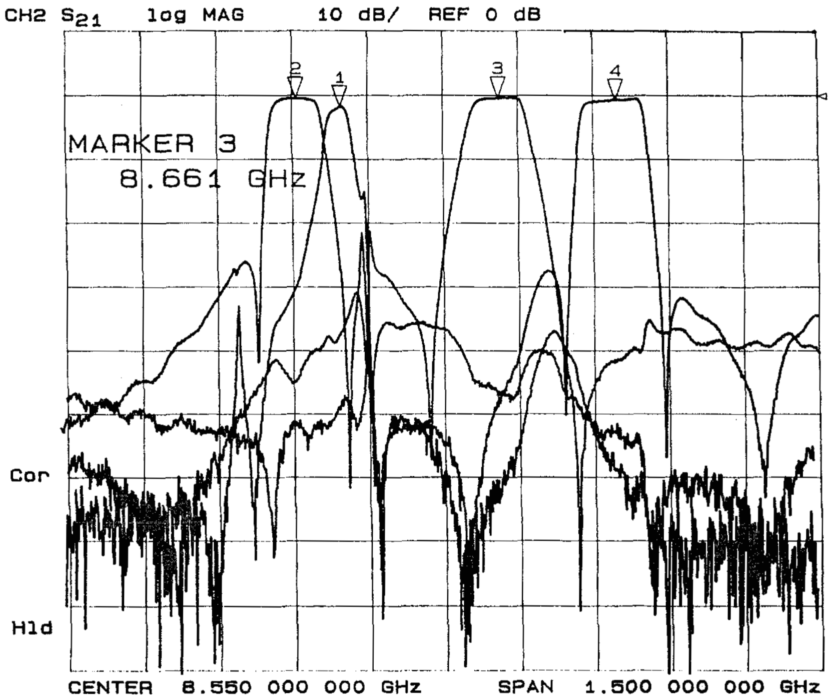


Fig. 15. Measured performance of the HTSSE-II multiplexer shown in Fig. 14. The performance matched with the theoretical analysis reasonably well. The narrow channel simulates a beacon as is commonly used in communication satellite multiplexers.

manifold opposite to the multiplexer filter, optimized in order to match the manifold well.

Using the four-pole, elliptic function filters and the waveguide/coax manifold, the multiplexer was optimized using the same software models employed on the previous eight-channel C-band output multiplexer. Fig. 13(a) shows the coupling matrix for the four-pole filter design used as a starting point in the optimization. Although the spacing from filter to filter was well predicted, it was expected that the coaxial coupling would need empirical adjustment due to the unavailability of accurate models for the probe into the waveguide manifold. Fig. 13 shows the results of the optimization for the 4-channel multiplexer.

B. Experimental Results

The multiplexer was built using the planar HTS filters and the optimized manifold as shown in Fig. 14. Initially the filters were tuned individually off the manifold in order to ensure approximately correct adjustment. Upon connection to the manifold, considerable adjustment was required to the coaxial connection from filter to waveguide, due to the uncertainty in the characteristics of the junction. In addition, screws into the manifold opposing the filter junction were employed in order to easily adjust coupling to the waveguide. As with any directly combined multiplexer, the filters were tuned to match the junction characteristics and to account for effect due to adjacent filters. Tuning was performed at 80 K.

Fig. 15 shows the multiplexer performance using the HTS filters and the combining manifold at 80 K. The computed design was reasonably well reproduced, but with more adjustment a closer match could be made.

V. Conclusion

NRL's HTSSE program spearheaded the development of microwave devices utilizing high temperature superconductors. A large variety of microwave components and subsystems with potential satellite applications were successfully developed. Specifically, significant progress was made in the area of high performance, narrow band filters, and multiplexers used in communications satellites. Some of the HTS resonator and filter configurations were described in this paper. Excellent performance and tunability (required for precise frequency adjustment) were demonstrated. The miniature multiplexer discussed in this paper demonstrates the viability of this technology for space applications, and its characteristics closely follow real life satellite payload design requirements (e.g., steep elliptic function filters).

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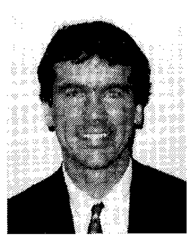

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