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# Advanced Filter Technology in Communication Satellite Systems

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*Abstract* - A rapid increase in global demand for voice, video and data services has created explosive growth in the capabilities of commercial communication satellites. Because present communication satellites often use hundreds of filters in their payloads, filter and multiplexer technologies dictate most of the performance of the transponders. This paper provides an overview of current filter technologies commonly used in the satellite industries, and highlights some efforts in development of the next generation filters in space applications.

## 1. INTRODUCTION

In the nineteen sixties, commercial satellite communication became a reality and provided significant changes to microwave designers. It required many technological advances to reduce mass and volume of the satellite payload. At the same time, increasingly stable components were needed coupled with more efficient delivery of higher Effective Isotropic Radiated Power (EIRP). In those communication systems, the available (allocated) frequency spectrum is the primary consideration. Since typical high power amplifiers are non-linear, this necessitates the channelization of the allocated frequency band into a number of channels (transponders). A simplified block diagram of a communication payload is shown in Fig. 1. The payload typically contains receive antennas, wide band filters, receivers (which include very stable, low phase noise local oscillators), input multiplexers, high power amplifiers, output multiplexers, and transmit antennas.

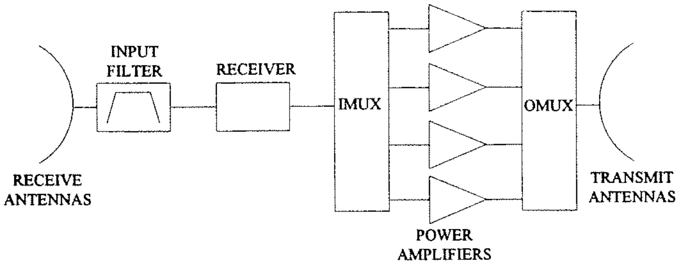

FIGURE 1 - Simplified payload of a communication satellite

Antennas, receivers, switching networks, and high power amplifiers are wide band, and therefore have minimal impact on the amplitude and phase of the transponder. However, individual filters in filter banks (multiplexers) are relatively narrowband (1% to 3%) and introduce significant deviations in a transmission, both in amplitude and phase (group delay). As a consequence, those filters govern the characteristics of the communication transponder and their design is extremely important. For this reason, the multiplexers are usually a focus of design of a satellite transponder, and a significant effort is generally made to optimize their characteristics. At the same time, minimum mass and volume are needed.

## 2. INPUT FILTERS

The input preselect filter eliminates spurious signals leaking into the receiver and mixer, and determines the overall noise figure and dynamic range of a transponder. Typically, a waveguide filter assemble (combination of bandpass and lowpass filters) or mechanical tunable filter (such as combline or interdigital filter) is used for its low insertion loss and wide rejection band. Quite often, the same antenna is used for both transmission and receiving. In that case, a waveguide diplexer replaces the functions of a input filter.

## 3. RECEIVER FILTERS

Almost all receivers are of the superheterodyne configuration in which a mixing process is involved. A simplified receiver block diagram is shown in Fig. 2. The mixing process may involve one or more conversions which can be either up or down conversion.

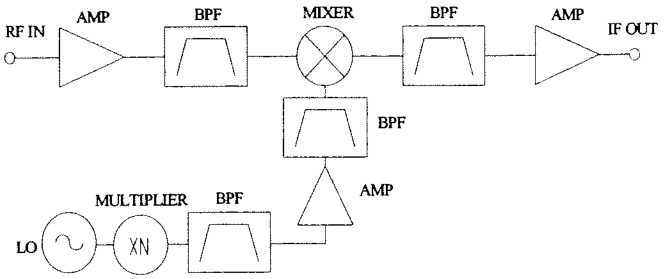

FIGURE 2 - Typical block diagram of a commercial receiver.

*RF / IF FILTERS*

The RF and IF filters reduce the spurious response of the receiver due to the undesired mixing of the LO and subharmonics. Because of their wide band characteristics, relatively low Q miniature filters can be used without costing too much from the gain budget of the receiver. The most popular RF / IF filters are the microstrip edge-coupled filter and miniature combine filter.

Edge-coupled filters are easily designed and implemented[1]. However, there is a parasitic passband at twice the center frequency due to the unequal phase velocity of the even and odd mode. Several techniques were proposed to suppress the second passband. The most common method is to overlap the resonators[2] as shown in Fig. 3. A 50 dB rejection at the second harmonic can be easily achieved. With the advancement in soft substrate and CAD tools, more designers are using microstrip interdigital filter in the RF / IF chain of the receiver to accomplish a more compact design with superb performance.

FIGURE 3 - 4-section edge-coupled filter, (a) conventional. (b) modified.

To remove spurious responses close to the receiving passband, a notch filter is often required in a receiver design. It is sometimes included in the IF filter by means of external distributive resonators. Often, it is a stand alone design utilizing distributive or dielectric resonators[3], as shown in Fig. 4.

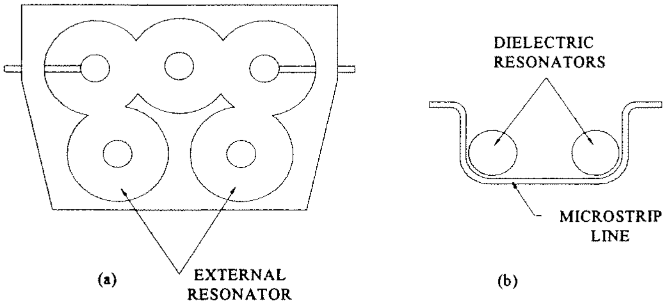

FIGURE 4 - A 2-section notch filter (a) combines with a 3-pole combline design. (b) utilizes dielectric resonators coupled with a microstrip line.

*LO FILTERS*

Depending on the frequency of the oscillator and the frequency multiplication scheme, the LO filters typically range from 100 MHz to 5 GHz. Since insertion loss and loss variation are not a concern for this single frequency reference signal, low Q quasi-lump element filters are often used for their small size and ultra-wide stopband at the low end of the spectrum. With appropriate choices of topology and packaging, rejection band as wide as 10 times the center frequency is often achieved. As frequency increases, one would find more distributive filters along the LO chain. Sometimes, a lowpass-highpass diplexer is used for the last filter in the chain to assure a broadband matching for the mixer.

## 4. INPUT MULTIPLEXERS

The typical configuration of a satellite input multiplexer is shown in Fig. 5. In these multiplexers, absolute insertion loss is not a constraint. This is due to the fact that the noise figure of the satellite transponder is almost solely determined by the front end of the receiver and any insertion loss after the receiver contributes very little. For this reason, the relatively lossy circulator coupled approach is employed providing a maximum flexibility in terms of ease of realization as well as mechanical layout. The high Q factor of the filters is still needed since, this also determines an insertion loss variation across a communication channel. Typically, a response as flat as possible is needed (close to ideal brick-wall filter). Also, to improve the group delay characteristics of the channel (as well as amplitude), input multiplexers employ circulator coupled all-pass networks in cascade with the filters (equalizers) to achieve the required passband performance.

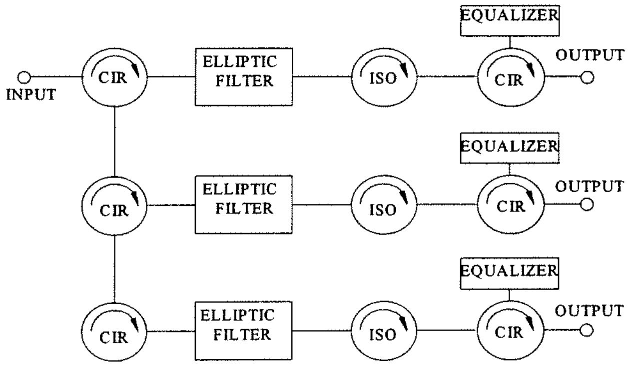

FIGURE 5 - A block diagram for a 3-channel Input Multiplexer.

The input power to these multiplexers is typically +10 dBm. At such a low power, heat dissipation and conduction are not constraints, and therefore the dielectric resonator filters described in subsequent paragraphs are ideally suited for these applications.

*DUAL MODE DIELECTRIC RESONATOR FILTERS*

Due to developments in ceramics technology and the general availability of high performance, temperature stable ceramics, dielectric resonators are utilized in the high performance filter designs. Additional miniaturization is obtained by combining the dual-mode cavity technique with dielectric resonator technology[4]. The temperature coefficient of the dielectric can also be chosen to compensate the thermal expansion of the filter housing, resulting a small and lightweight filter with excellent electrical and temperature characteristics. A typical dielectric dual-mode configuration is shown in Fig. 6.

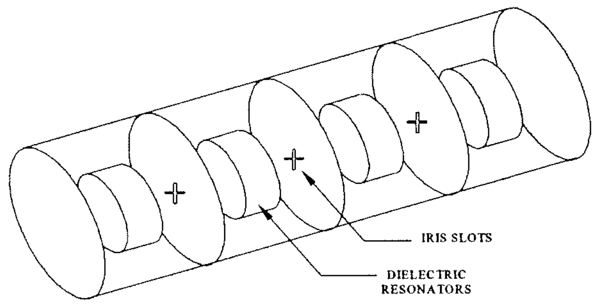

FIGURE 6 - Dual-mode dielectric resonator loaded cavity filter configuration. Shown here is an 8-section quasi-elliptic filter.

Because of the evanescent nature of the hybrid electromagnetic fields in the cavity, filters are less sensitive to frequency related iris dimension changes. In essence, to realize the same response at a different frequency, practically identical iris dimensions are required. This is extremely convenient in manufacturing.

## 4. OUTPUT MULTIPLEXERS

The output multiplexers (often contiguous) are traditionally waveguide filters fabricated of thin-wall INVAR and GFRP (Graphite Fiber Reinforced Plastic) technologies to reduce weight while providing temperature stability. Similar to the input multiplexers, most output multiplexers utilize the dual mode approach pioneered by Atia and Williams[5] (using degenerate cavity modes) to reduce weight and to realize conveniently high performance elliptic function filters. However, since the output multiplexers operate at a much higher power level (sometimes over 200 W at Ku-band), insertion loss is a critical design parameter and dielectric resonators are generally not suitable. In addition, at such a high power environment, thermal design of the multiplexer assemble becomes as important as the electrical design. Heat straps are strategically placed to provide a effective thermal path to the spacecraft panel and the heat pipe. Thermocouple and heater are also inserted to minimized the temperature fluctuation over the operating cycle.

## 5. FUTURE TECHNOLOGY

The current state-of-the-art for satellite multiplexer applications is the use of dual-mode cavity and dielectric resonator filters. These filters provide a quality factor Q of at least an order of magnitude higher than that of other commonly used microwave filters such as the combline and interdigital filters. Nevertheless, the dual mode cavity resonators are highly labor intensive to produce and have the drawbacks of relatively large size, mass and high production costs.

An apparent alternative to the cavity and dielectric resonator filters is the use of single mode planar filter structures implemented in stripline or microstrip such as those used in the receivers. These filters offer extremely small size and low mass as well as radically reduced production costs as a result of printed circuit fabrication techniques. However, these planar structures fall well short of meeting the stringent performance requirements for satellite filter applications in two very basic and important ways.

The first drawback to the conventional single mode planar filters is the characteristically low Q which is typically 2 order of magnitude lower than that of a cavity resonator. The second drawback is that it is very difficult, if not impossible, to realize the elliptic function, group delay equalized responses required for satellite filter bank applications.

### *DUAL-MODE PLANAR FILTERS*

A new class of dual-mode planar filter structures that is made practical due to the recent development of the High Temperature Superconductors (HTS) was investigated[6]. Figure 7 shows the dual-mode square and circular patches, and some possible configurations that can be used to realized the quasi-elliptical responses. The asymmetrical features are added to the patches to facilitate the coupling between the dual orthogonal modes. Such resonators have been modeled and tested on microstrip and stripline configurations.

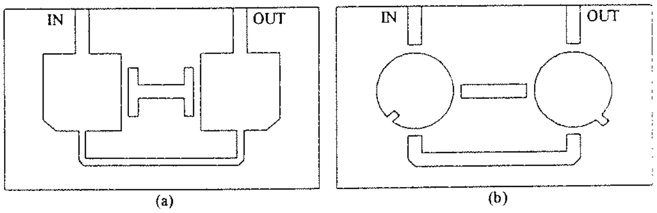

FIGURE 7 - A possible dual-mode planar filter configuration utilizes (a) square patches, and (b) circular patches.

### *MINIATURIZED MULTILAYER FILTERS*

To further reduce the size and weight of the HTS planar filters, a miniaturized multilayer configuration is developed[7]. Figure 8a shows a 4-section filter realized by stacking the stripline dual-mode planar resonators on top of each other. Coupling between the dual-mode sections is achieved by interlayers of irises or slot openings. Superconducting films of patches, irises and ground planes are deposit onto layers of substrate in a designed pattern.

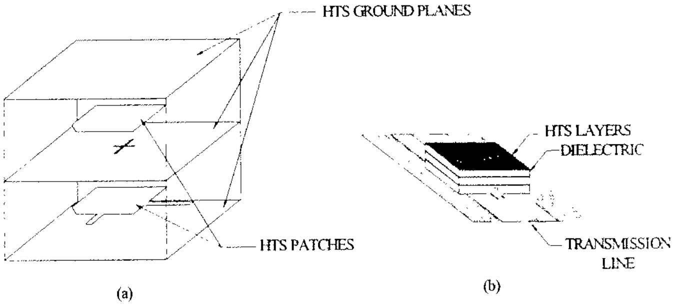

FIGURE 8 - (a) Multilayer dual-mode filter configuration. (b) Same filter in flat-pack surface-mounted technology.

Similar to the cavity resonator, the new filter structure facilitates the practical elliptic function and group delay equalized responses required for satellite applications. In addition, the stacking configuration provides the smallest possible size of the filter. For example, a filter of this configuration in C-Band occupies less than 1 % in volume as compared to its dielectric resonator counterpart. More importantly, it can be manufactured in form of a flat-pack surface mounted chip (see Fig. 8b) which could be easily integrated into the payloads via microstrip or coplanar waveguide connections. Table 1 summarizes the advantages of this class of HTS filters.

| | weight* reduction | size* reduction (in volume) |
|---|---|---|
| single mode waveguide | - | - |
| dual-mode INVAR & EFRP | 50 % | 50 % |
| dual-mode dielectric resonators | 50 % | 80 % |
| HTS dual-mode planar with fixture | 75 % | 60 % |
| HTS flat-packed dual-mode multilayer | 85 % | 97 % |

* as compared to previous technology

TABLE 1 - Weight and size comparison of various filter technologies.

### *HTS / DIELECTRIC FILTERS*

The planar filters are limited to low power applications because of the relatively large current density along the edges of the stripline. Several filter configurations based on high dielectric constant, low loss ceramics, combined with HTS films have been developed[8]. Figure 9 shows two different configurations of hybrid superconducting dielectric resonator filters by using "full puck" and "half cut" resonators. To enhance the power handling capability of the structure, a small spacer is placed between the resonators and the HTS films such that the current density on the HTS is below the critical value. This type of filter structures are capable of transmitting signal up to 20 watts which is above the typical transmit power of a LEO (Low Earth Orbit) satellite.

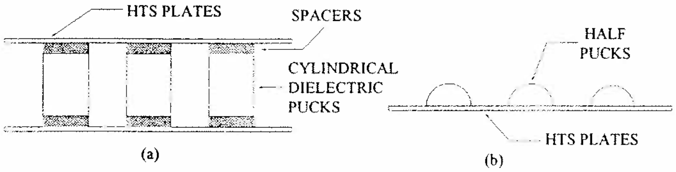

FIGURE 9 - HTS / Dielectric resonator filter configurations with (a) full pucks, and (b) half pucks.

## 6. SUMMARY

Filter technology has improved drastically over the years. Miniaturization and cost reduction are critical criteria for successful designs. While miniature ceramic coaxial resonators technology dominates the cellular PCS market, superconducting filters are believed to be the future in space applications. Several improvements have to be made for the HTS designs to be commercially useful in space.

(1) Although the cryocooler has been reduced to an acceptable size, the efficiency is still quite poor. In the space environment where the number of solar panels is limited, this poses a serious technical barrier for the usage of HTS systems.

(2) The superconducting transition temperature for various oxides is roughly 100 degree kelvins. For the past decade, scientists around the world are trying to improve this number. Should the critical temperature arise to a temperature where the current heat pipe and cryocooler can operate efficiently, HTS designs will replace most of the existing filters in the transponder.

(3) The critical current density of the HTS film is still too low for the output filters. Several methods have been demonstrated to enhance this critical density in dc applications[9]. It is not clear that the same benefits can be obtained in RF / microwave frequencies.

Any breakthrough in one of the areas will be a major advancement in filter technology for future space communication systems. Figure 10 summarizes the trend of the filter technologies over the past years.

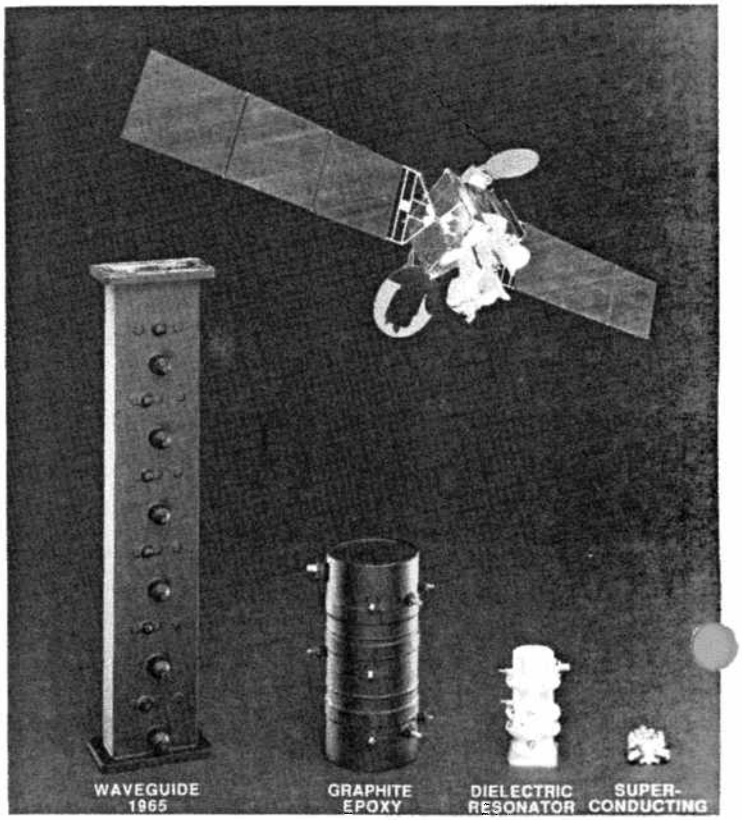

FIGURE 10 - Improvement of filter technologies over the years.

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[1] see e.g. G.L. Matthaei, L. Young, E.M.T. Jones, "*Microwave Filters, Impedance-Matching Networks, and Coupling Structures*", Ch.10. Artech House, 1964.

[2] A. Riddle, "*High Performance Parallel Coupled Microstrip Filters*", IEEE MTT-S Digest, p.427-430, 1988.

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[7] S.J. Fiedziuszko, J.A. Curtis, "*Multi-Layered Planar Filters Based on Aperture Coupled, Dual Mode Microstrip or Stripline Resonators*". IEEE MTT-S Digest, p.1203-1206, 1992. U.S. Patent 5,484,764 (1996).

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[9] see e.g. M. Maley et. al. "*Enhancement of the Transport Critical Current by High-Energy-Proton-Induced Heavy ion Fission Fragments in High Tc Superconductors*", Bull. Am. Phys. Soc., vol. 40, p.499, 1995.