Design of high-power filters in waveguide technology

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In order to design a filter for a particular application, many issues must first be considered. Which technology will be the most convenient? What design technique will provide better results for a particular set of frequency specifications? Once the device has been designed, will it fulfill all the (not only electrical) requirements? It is not always easy to answer such questions in advance. In this paper, we try to shed some light on these questions when our aim is the design of filters for high-power operation.

The implementation of a filter in a specific microwave technology depends on the needs of the particular application [1]-[5], with planar, coaxial, and waveguide technologies being the most common. Each technology has different properties, mass/volume, loss, power handling capability, cost, etc. (see Fig. 1), and there are a wide variety of techniques that allow us to design high-performance components for these technologies [6]. At low frequencies such as the L- or S-band, coaxial and ridge technologies are extensively used for low-pass and bandpass filters thanks to their compact size. However, when high-power handling is necessary, special attention must be paid during the design, manufacturing, and tuning of the filters. Therefore, despite its mass and volume, the waveguide is one of the most advisable solutions to implement microwave components when high-power handling capability is a requirement, even in applications where these features (mass and volume) are critical, such as in the payload of communication satellites. Moreover, waveguide technology benefits from a low insertion loss compared to the aforementioned microwave technologies.

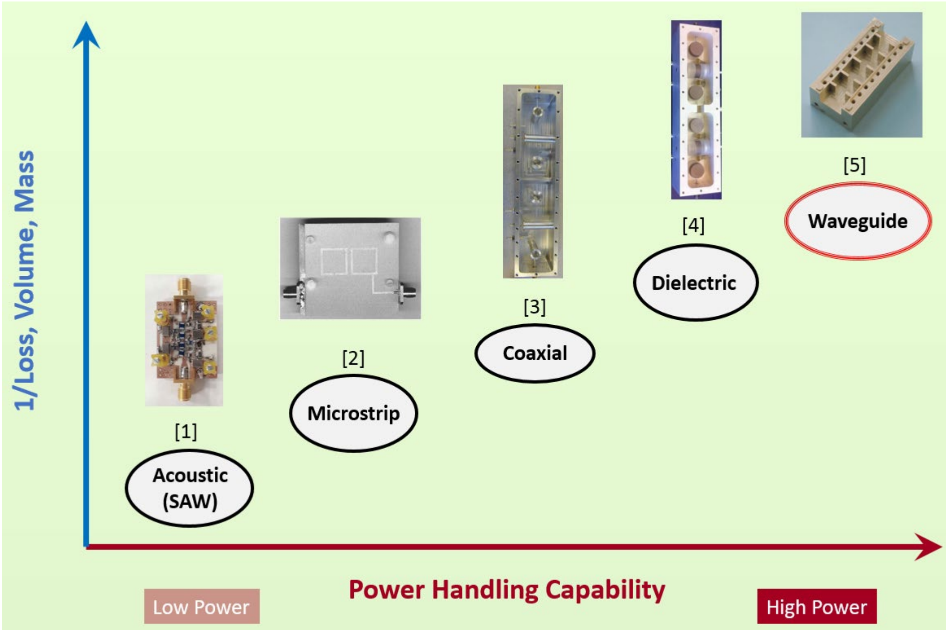


Figure 1. Technologies employed for the implementation of microwave filters, including an example of each technology. Classification according to different properties: power handling, loss, volume, and mass.

Several issues should be considered when designing a high-power filter in a rectangular waveguide technology, including multipactor, corona, passive intermodulation (PIM), and thermal effects [7]. Taking into account that one of the most important applications of high-power waveguide filters is their use in satellite payloads, in this paper we focus on mutipactor breakdown since it is the most limiting phenomenon when filters are used onboard a space platform. The multipactor effect is a breakdown discharge that occurs in microwave devices operating at high power levels and in vacuum conditions [8], [9]. It is caused by the formation of an electron avalanche originating when free electrons are accelerated by radiofrequency (RF) fields and collide with the metallic walls of the device with enough energy to release secondary electrons from the surface. If the electrons come into resonance with the field, this process repeats itself until a high electron density is achieved. This results in the disturbance of the signal, such as distortion, additive noise, high reflections, and, ultimately, a destructive discharge that can damage the device [10]. Therefore, the multipactor effect depends on the following constraints: vacuum condition, frequency of operation in conjunction with the geometry of the component (mainly the minimum mechanical gap), RF voltage applied, and surface characteristics (material, roughness, etc.).

The concept of *high-power* is imprecise, since the term *high* or *low* depends on the application and the specific use of the device. Some may consider hundreds of watts to be high power whereas others need kilowatts, perhaps at different frequency ranges or across different technological implementations. However, there are a few elements that escape this ambiguity, such as that high-power filters implemented in planar technology (e.g., microstrip filters) will never achieve the values that can be easily accomplished by waveguide filters, as deduced from Fig. 1, and, in fact, waveguide can be considered the preferred technology for high-power handling.

Our focus in this paper is on a future generation of waveguide satellite filters in payloads that need to handle increasing bit-rates and numbers of channels and, hence, the filter must be prepared to withstand power levels not used in the past and even the several-kilowatt level of the combined signal. The proposals found in an extensive literature review reveal interesting approaches both in filter designs and in coatings, in some cases for virtually multipactor-free filters. Effects limiting the power handling in waveguide filters are also discussed in the paper, which also reviews some general aspects of paramount importance when high power comes into play, such as thermal control, precise multipactor simulation and measurement, and materials used.

Low-pass filter design

In order to achieve a low-pass frequency response in rectangular waveguide technology, the classical E-plane corrugated filter is the usual solution as it achieves a wide stop band for the fundamental TE_{10} mode [11]. Its topology consists of cascaded high- and low-impedance waveguide sections and its design method has been improved during the last decades in order to avoid long optimization processes [12]-[15]. Unfortunately, there exists an intrinsic trade-off between the bandwidth of the stop band and the minimum mechanical gap that is required in a corrugated filter, and this impedes the simultaneous achievement of low-pass corrugated filters with large mechanical gaps and a wide stop band. In order to improve the high-power (multipactor) behavior of these devices, the low-pass filter response can be implemented by means of posts with circular shapes that enhance the power handling of the classical structures based on capacitive discontinuities [16], see Fig. 2. Another approach to improving the filter's immunity to multipactor was proposed in [17], where a device consisting of a classical high-power corrugated low-pass filter is cascaded with a quasi-periodic structure based on the Bragg reflection phenomenon whose period is tuned to reject the undesired intrinsic spurious passbands of the low-pass filter [18]. The technique allows the minimum gap of the corrugated filter to be kept wide, which, along with the smoothness and the large gap of the quasi-periodic structure itself, enables high-power operation in the whole device, while the spurious passbands for the TE_{10} mode are suppressed.

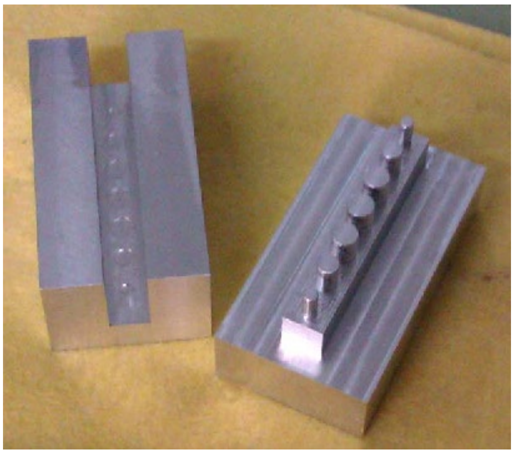
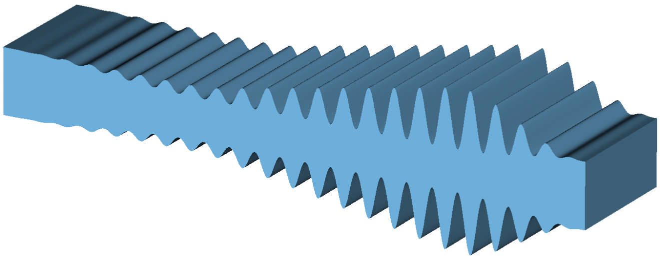


Figure 2. Low-pass waveguide filter implemented with rounded posts to improve power-handling capability [16].

In recent years, a new alternative has arisen which consists of multiple E-plane bandstop elements of sinusoidal profile in a quasi-periodic structure arrangement, where the tuning of the rejected frequencies is achieved through the height of the bandstop elements and not through the period of the structure (Fig. 3a). Windowing the quasi-periodic structure height allows the implementation of low-pass filters with deep levels of out-of-band rejection in a wide band, preserving a large mechanical gap [19]. Moreover, this technique was extended to achieve the rejection of not only the fundamental TE_{10} mode but also all other higher-order modes. This can be essential when the filter is embedded in a system where the power of the signals may be propagating not only in the fundamental mode. Indeed, it can occur, for instance, that the signal is coupled to other modes due to unexpected asymmetries produced during the fabrication process. These undesired modes can be suppressed by means of a two-dimensional arrangement of E-plane bandstop elements (following a sinusoidal variation both in the transversal and propagation direction of the profile [20]). This structure, based on the working principle of classical waffle-iron filters to reject the higher-order modes [21], permits the suppression of wide bands while keeping the high-power behavior. Another possible means to achieve this is by an ad-hoc reduction of the filter width [22]. This concept was initially employed in the design of inhomogeneous stepped-impedance corrugated low-pass filters [23] and, therefore, was not intended for high-power applications.

In addition to the mechanical gap, the use of smooth profiles in the previous devices enhances the high-power operation of the filter compared with classical stepped geometries [24], [25]. Indeed, the most critical areas are eliminated, since parallel-plate geometries are avoided, and the smoothness facilitates the deviation of the electrons to larger cavities, making the multipactor phenomenon less probable (Fig. 3b). In addition to their power handling behavior, smooth profiles are suitable for fabrication by electroforming and thus are a very good option if additive manufacturing techniques are employed. However, these types of profiles are not suitable for computer numerical control (CNC) milling, which is the method most commonly employed in the aerospace industry mainly due to cost and lead time. Therefore, these approaches to the design of filters have been recently reconsidered for implementing devices with stringent specifications (regarding frequency response and high-power handling capabilities) but also making use of step-shaped bandstop elements, see Fig. 4, to ease the fabrication by CNC milling [26] - [29]. In fact, from the thorough analysis performed in [30], it can be concluded that, considering appropriate geometries of the bandstop step-shaped elements, it is possible to fabricate (by CNC milling) low-pass filters addressing a wide stop band and featuring in practice (almost) unlimited power handling constraints (and, consequently, no need for costly high-power testing!). As an example, a device designed for Ka-band multibeam satellite payloads is shown in Fig. 5, and its main features are compared with respect to the classical solution in Table I. This kind of filter is now accepted by the European satellite industry as a new class of low-pass high-power filters of high market impact [26].



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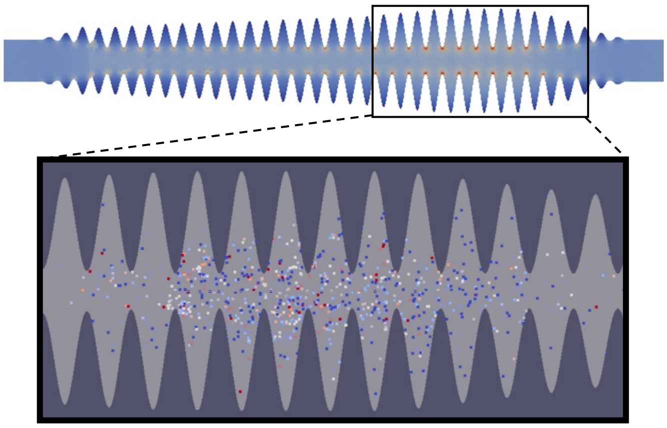

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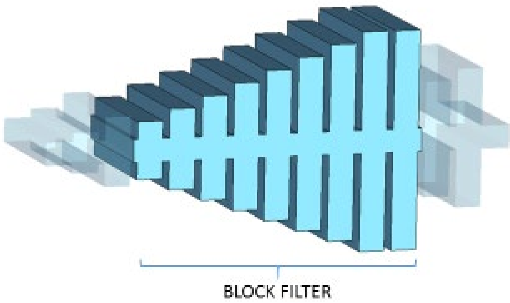
Figure 3. a) High-power low-pass filter consisting of windowed bandstop elements with smooth profile and b) critical area of a filter with smooth profile, i. e., region where the maximum electromagnetic field takes place (top), and detail of the high concentration of electrons in this region when high-power simulations (using SPARK3D) are performed (bottom). In filters with smooth profiles, the critical areas are not parallel-plate geometries and, therefore, the electrons are easily deviated, reducing the probability of multipactor.



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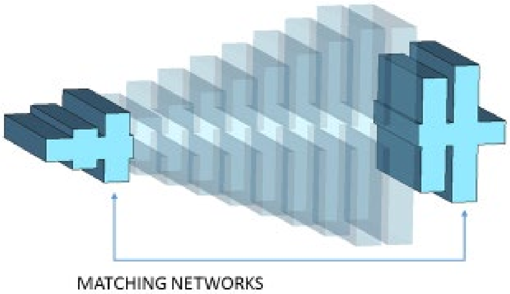

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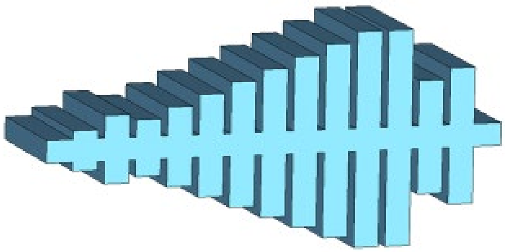

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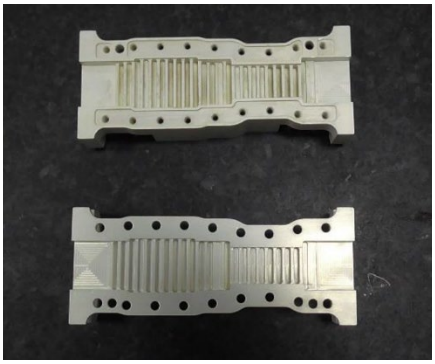
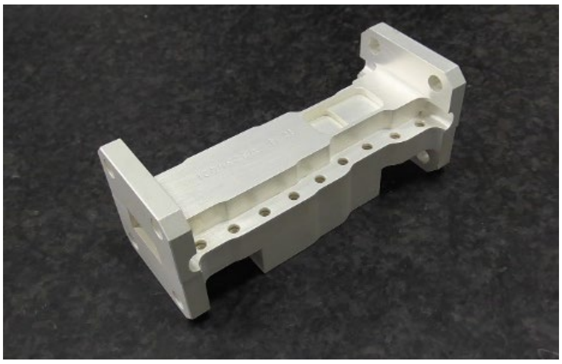
Figure 4. Schematics of a high-power low-pass filter designed using step-shaped bandstop elements [28]: a) block filter used to obtain the required attenuation in the stop band, b) matching networks required to achieve the in-band return loss, and c) final filter.

Table I. Main features of the filter depicted in Fig. 5.

	Classical waffle-iron filter	Filter based on [30]
Length	79.6 mm	55.8 mm
Longitudinal slots	12 x 5	NO slots – Easy Fabrication
Minimum gap	0.65 mm	2 mm
Insertion loss (considering silver)	0.21 dB	0.11 dB
Power threshold (considering silver)	2.1 kW	19 kW





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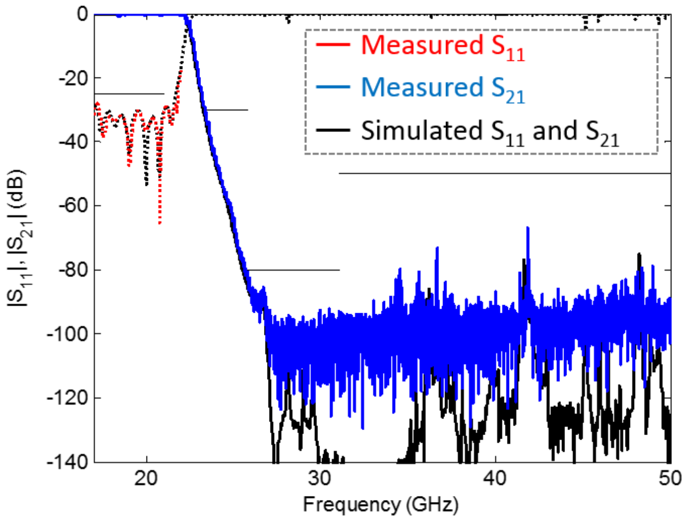

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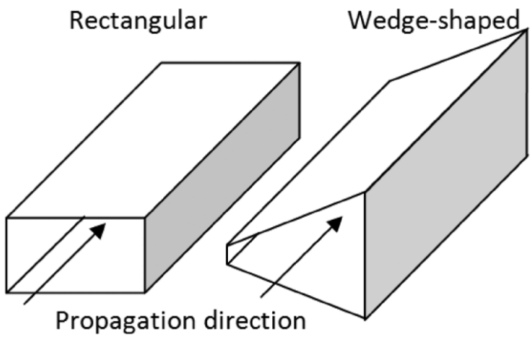
Figure 5. Low-pass filter designed following [30]: a) fabrication in two halves, b) assembled filter, and c) frequency response. European Space Agency (ESA) Contract No. 4000116931/16/NL/MH/GM, ITI B00017002 Project “Compact High-Power Ka-Band Low-Pass Filters for Multibeam Satellite Payloads,” developed by AURORASAT SL, NOVALTI SA, and UPNA (customer: TESAT Spacecom GmbH).

Bandpass filter design

The classical solution to designing a filter with a bandpass frequency response is the inductively coupled rectangular waveguide filter. This filter consists of $\lambda/2$-long waveguide resonating cavities coupled through inductive irises, which act as impedance inverters. The first design method for filters of this kind was based on a lumped-element prototype [31], which provides good results for narrowband filters. Better results were achieved using distributed networks [32] and, additionally, several methods have been proposed in the last decades to achieve devices which are able to operate in a wide frequency range [33] - [36]. In this type of filters, the maximum electromagnetic field levels are achieved in the center of the resonant cavities, where large dimensions can be found and, therefore, high-power handling operation is easily achievable. Moreover, if larger values are required, alternatives to the rectangular waveguide such as the wedge-shaped waveguide [37], see Fig. 6, can be used to implement the waveguide resonators and increase the power operation [38].



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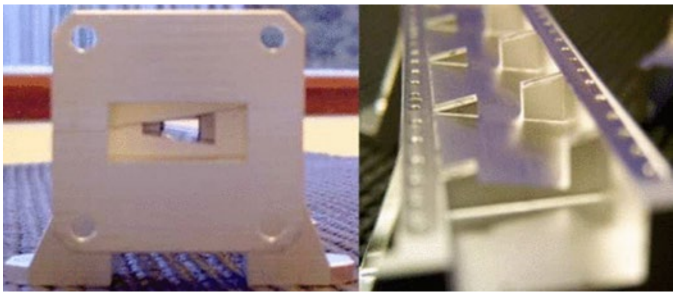

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Figure 6. a) Schematics of a rectangular and a wedge-shaped waveguide and b) bandpass filter prototype implemented in a wedge-shaped waveguide [38].

However, it is not always possible to fulfill the frequency specifications or the footprint requirements with a classical inductive filter solution and a vast number of topologies have been published in the last decades to accommodate specific requirements of different applications. Most of them improve the frequency behavior by adding geometries that include small dimensions and/or screws which can be used to tune the frequency response [39] and, therefore, can compromise very high-power operation. Moreover, dielectric materials can be used to reduce the size of the structures even further. In this case, it is essential to know the main features of the dielectric [40] and to wisely use it in order to maintain or even increase (up to a point) the multipactor level [41], [42]. An example can be seen in Fig. 7, where the critical area of a helical resonator filter is protected with dielectric material to increase power handling (to values around 100 W). In addition to the multipactor effect, it is also important to take into account the power dissipated inside the dielectric material, since it can also limit power handling if the heat generated in the dielectric is not conveniently transferred to the filter housing [43], [44].

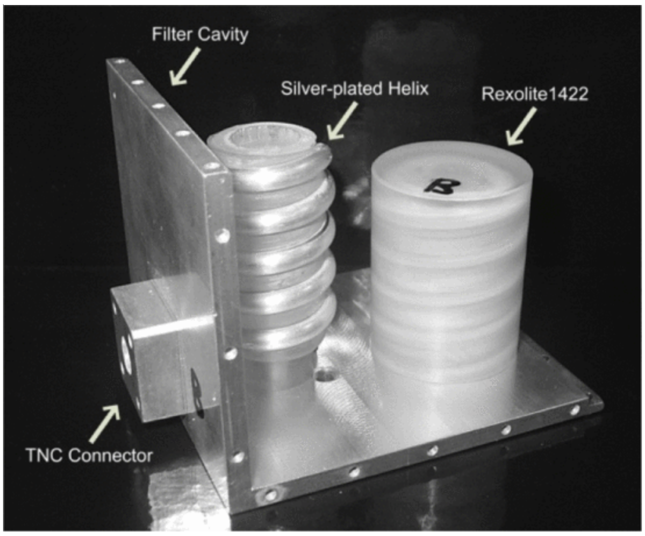
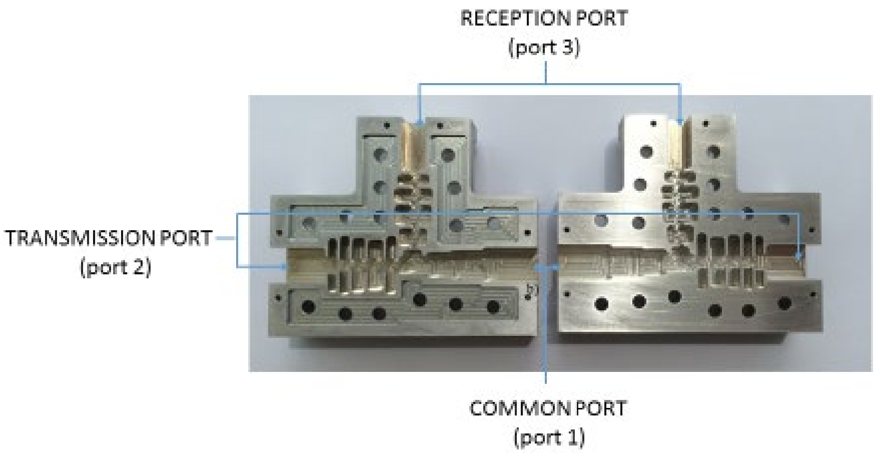


Figure 7. Helical resonator filter with dielectric (Rexolite 1422) in the multipactor critical areas to increase the high-power handling capability [41].

Another important issue to consider when designing a bandpass filter is out-of-band performance. Unfortunately, in most bandpass waveguide filters (such as the aforementioned classical inductive devices) the upper stop band is degraded by the replicas of the passband and, hence, it is not possible to achieve a wide spurious-free response. In [45], [46], the dimensions of each resonator that composes the filter are modified to shift the replicas up to higher frequencies, improving the out-of-band characteristics of these devices while the fundamental resonance is kept centered around the passband design frequency. These filters, known as inhomogeneous inductive waveguide filters, are able to achieve stop bands free of the first replica. If a wider spurious-free band is required, low-pass structures can be used to achieve the rejection up to the frequency of interest. An example of a bandpass filter based on a combination of classical low-pass and high-pass structures was proposed in [47]. However, as has been previously explained, the use of classical low-pass devices in a rectangular waveguide technology (such as the E-plane corrugated filter) with a wide stop band implies a low minimum mechanical gap and, therefore, low high-power levels. In [48], high-power bandpass filters with a wide stop band are proposed. In order to achieve the bandpass frequency response, the technique combines a high-pass response obtained by a smooth variation of the width of the rectangular waveguide [49] with the low-pass response accomplished by [19], which makes it possible to obtain simultaneously a structure that features high-power handling capability and a wide stop band. The combination is done in such a way that the length of the bandpass filter is not increased in comparison with the low-pass structure. Moreover, the concept has been also developed in the step-shaped version of these filters and, as is shown in Fig. 8, even included as part of a compact diplexer with stringent specifications [50]. This device consists of two bandpass filters which can handle more than 10 kW, even with aluminum as the material for the multipactor simulations.



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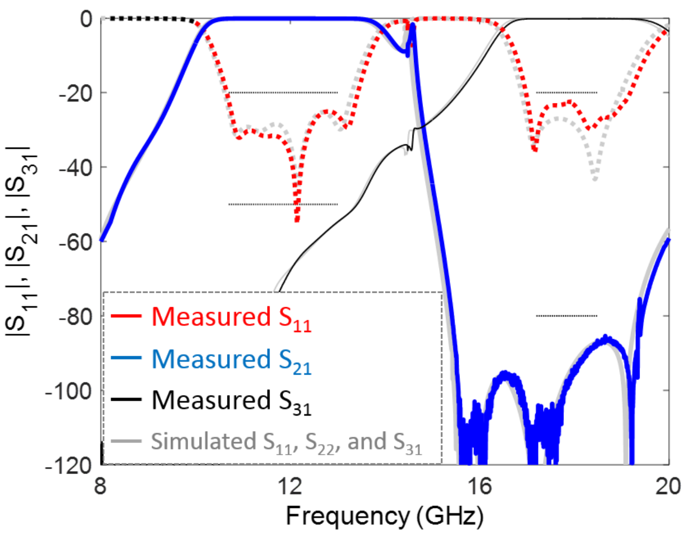

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Figure 8. a) Photograph of the unassembled diplexer fabricated by CNC milling in aluminum consisting of two bandpass filters and b) diplexer frequency response [50].

Multiplexers and multicarrier scenario

In a system, a multiplexer is used to combine several narrowband signals into a wideband aggregated signal. This occurs, for example, at the output section of a broadcast communication satellite payload, where the narrowband amplified channel signals are combined to be transmitted through a common antenna [51]. Several configurations can be used to implement a multiplexer, such as hybrid-coupled multiplexers, circulator-coupled multiplexers, directional filter multiplexers, and manifold-coupled multiplexers [52].

As is detailed in [53], manifold multiplexers permit the achievement of demanding frequency specifications in terms of insertion loss and group delay response in a compact size. When designing a manifold, it is necessary to consider the effect of the filters included in each channel and, therefore, this greatly increases the difficulty of implementing manifolds which operate in a large bandwidth or with a large number of channels. Another inherent disadvantage of this configuration is the lack of flexibility, although tunable reactive elements can be introduced along the manifold to obtain a reconfigurable multiplexer [54]. In spite of this design complexity, solutions have been proposed to facilitate the task [55], [56], and the manifold approach is the preferred solution when compact size, low insertion loss, and high-power handling capability are required (see Fig. 9).

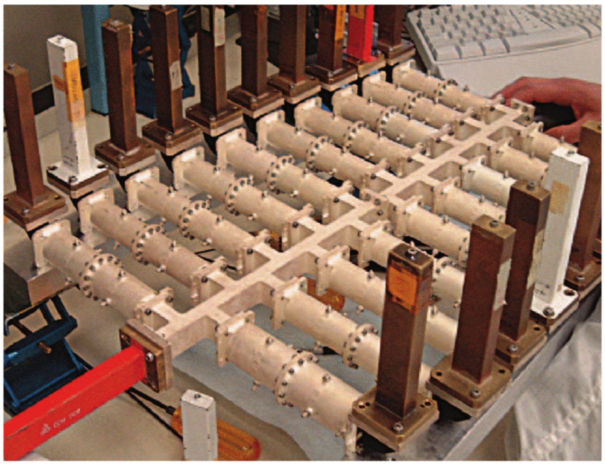


Figure 9. Photograph of a manifold-coupled multiplexer with 19 channel filters [53].

The estimation of the high-power handling capability of a device operating with a multicarrier signal is more complex than in a single-carrier scenario (which will be addressed in the following Sections). As a first approach, the multipactor power threshold can be determined simply as $K^2 \cdot P_{sc}$, where K is the number of carriers and P_{sc} is the single-carrier breakdown peak power. This calculation assumes that the envelope of the multicarrier signal is that generated when all the carriers are in phase. This is an unlikely situation (less likely as K increases) and it provides the most pessimistic scenario [57]. Therefore, this conservative approach can lead to unnecessarily oversizing of the design to avoid risks. The 20 gap-crossing rule [58] is a different approach which can provide a better estimation, although more complex methods have to be used to get accurate values in this intricate situation [57], [59].

Material considerations

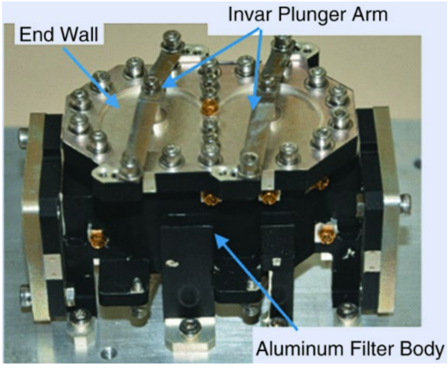
The first commercial satellites implemented waveguide filters and multiplexing networks using Invar [51]. This material features an excellent thermal stability and, therefore, it has been widely employed for decades in space applications, where RF components must ensure stable behavior over a wide temperature range (typically -10 to +75 ºC). However, it has also some disadvantages such as its mass (i.e., the density of this metal is high and this is an important drawback in applications where this issue is critical). Moreover, Invar's thermal conductivity, which is also a significant consideration when implementing high-power devices, is not as good as other alternative metals. In high-power applications, resistive heating can be one of the main sources of heat and, therefore, it must be efficiently conducted outside the waveguide cavities to be dissipated. Since this does not easily occur in Invar devices, other materials have also been employed.

In Table II, a comparison between different parameters of Invar and aluminum is presented. Although the specific values may depend on the particular alloy employed, it can be clearly inferred that an aluminum device will have a reduced weight (by a factor of close to 4) when compared with an Invar counterpart. Moreover, aluminum has good thermal conductivity. These properties, along with its easy manufacturability (Invar is prone to warp or break up during machining) makes aluminum the preferred solution in many applications.

Table II. Comparison between material parameters of Invar and aluminum.

	Invar	Aluminum
Coefficient of Thermal Expansion (CTE) [ppm/ºC]	1,6	23
Density [Kg/m^3]	8050	2070
Thermal Conductivity [W/mK]	10	200

In demanding applications where stringent specifications are required, such as in communications satellites, filters fabricated in aluminum are usually silver plated to improve their conductivity and, therefore, reduce insertion loss. Aluminum also eases high-power operation since it reduces resistive heating, an important source of heat in high-power applications. The heat must be dissipated to avoid frequency drift produced by the change in the dimensions due to changes in temperature. As the thermal expansion coefficient of aluminum is not as good as Invar is (see Table II), several solutions have been implemented to compensate for the temperature variation and reduce or even completely eliminate frequency drift [60] - [62], see Fig. 10. In the future, development of new alloys with good thermal conductivity, density, and thermal expansion coefficients may help to reduce the effect of extreme temperatures in space [63].



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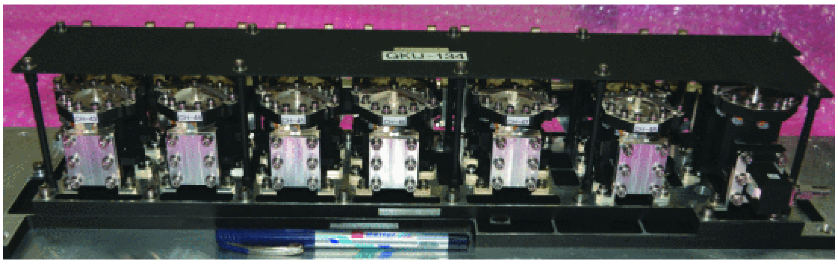

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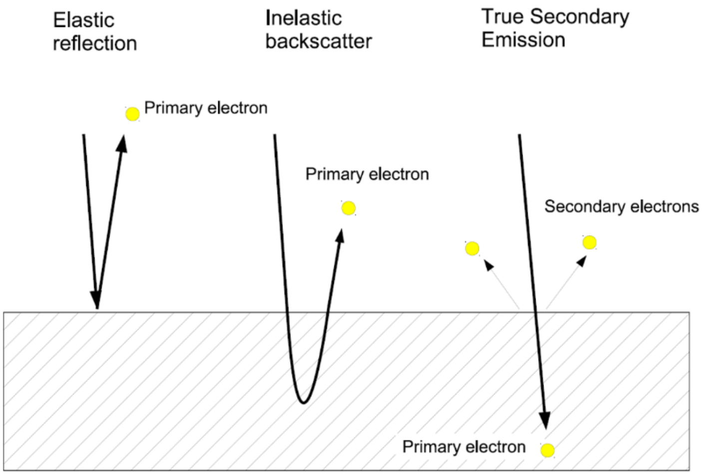
Figure 10. Ku-band band temperature-compensated devices: a) bandpass filter and b) 7-channel OMUX [62].

Another material parameter to be considered when manufacturing a device for high-power operation, since it determines the attainable power of RF components in space due to multipactor discharge, is the secondary emission yield (SEY). As can be seen in Fig. 11, this parameter is modelled considering the iteration produced when an electron hits a material: it can be elastically or inelastically backscattered, new electrons can be released (secondary emission effect), or it can be absorbed [64]. Appropriate materials to deal with the multipactor effect must feature a low SEY value while maintaining high conductivity (to reduce insertion loss) and good stability when operating in space conditions. Silver-plated aluminum components can fulfill these requirements since, in addition to the previously mentioned properties, silver has a good behavior when its SEY is analyzed [65] and can be easily deposited over an aluminum structure. However, it is important to note that both the specific type of silver and the plating procedure can have a considerable influence on the SEY. In fact, important efforts have been made recently to improve the coatings through micro- or nano-structured surfaces, which can reduce or even suppress the multipactor effect without having a significant impact on the RF performance of the devices [66] - [68]. The fabrication method used can also impact this parameter, as is explained in [69], where the roughness from additively manufactured surfaces is exploited to reduce the SEY and, hence, to increase the multipactor threshold.



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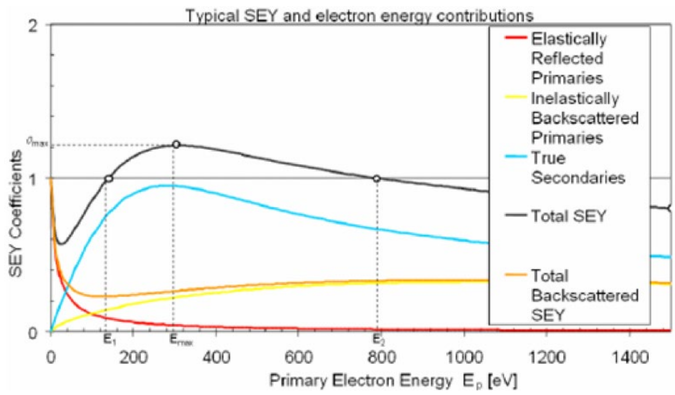

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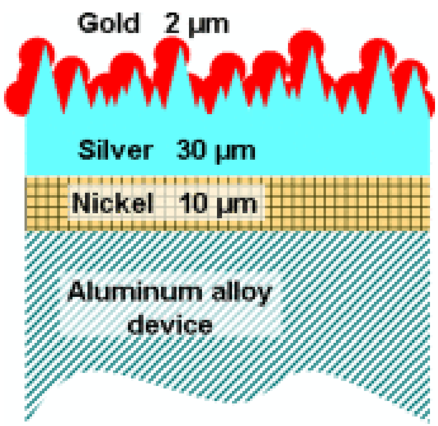

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Figure 11. a) Schematic of possible iterations between electrons and materials [64], b) example of the SEY curve of a material (decomposed in its different contributions) [64], and c) schematic diagram of the multilayer anti-multipactor coating proposed in [66].

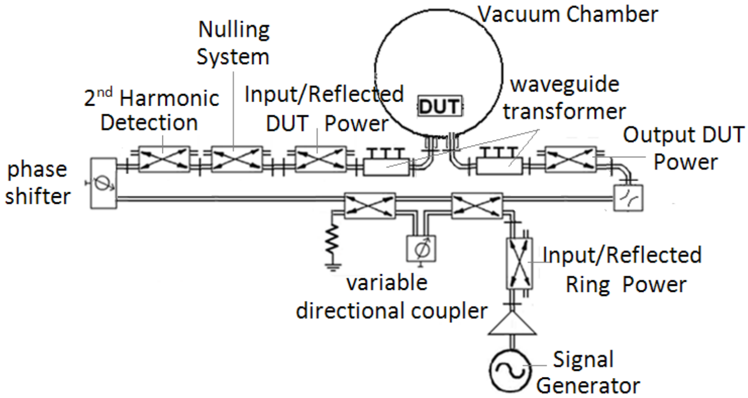
Multipactor software prediction and measurements

The parallel-plate model is a classical method to calculate the multipactor power threshold in waveguide filters. It was developed by the European Space Agency (ESA) [70] and it is based on a set of measurements of parallel plates with different gap sizes. In theory, the model is only applied to parallel-plate geometries of infinite size, but in practice it has been used in both industry and academia with waveguide components of very different sizes and shapes. On the other hand, specific methods to determine the multipactor breakdown voltage in real waveguide components have been developed in [71], [72] and they can be used to predict multipactor during the operation of these components.

Although the parallel-plate model provides an estimation of the threshold input power, in many cases it is too restrictive since the infinite parallel-plate theory results in the worst scenario possible (i.e., the lowest breakdown power value). In order to accurately analyze the multipactor effect, it is essential to know the real electromagnetic field distribution inside the microwave device. Hence, numerical particle-in-cell (PIC) codes which combine electromagnetic solvers and electron trackers can be used to calculate more precisely the threshold power of the multipactor from input parameters such as the frequency of operation, device geometry, and material SEY properties [73] - [75].

In order to perform multipactor measurements, an experimental setup such as the one described in [76] can be implemented. It must include different local and global detection methods, such as electron probes, a nulling system of the forward/reverse power at the carrier frequency, or harmonic detection methods. The electron probe detector is a local method (i.e., it is used close to the point of discharge) and it relies on the ability of a small positively charged probe to attract free electrons generated as a result of a discharge. The nulling of the forward/reverse power is a global method (i.e., the method indicates if a discharge is present somewhere in the assembly by superposing the input and the reflected signals, which are extracted from the experimental test bed with a directional coupler). Harmonic detection is another reliable global detection method. A multipactor discharge spreads energy over the spectrum, resulting in increased power in the harmonics that can be monitored to detect the presence of a discharge.

If it is necessary to increase the maximum power level available in a test bed to fully characterize devices with large multipactor threshold levels, advanced test beds can be designed [77], [78], [22]. For example, a ring resonator or travelling wave resonator can be assembled following the schematic shown in Fig. 12, which shows a ring resonator integrated into a multipactor test bed. Using this setup configuration it is possible to reinforce the field levels in the critical gap area of the device under test (DUT). In order to achieve it, three issues must be addressed: (i) the length of the ring must be an integer number of the wavelength at the operation frequency to ensure that the wave which enters into the ring and the one that is propagating along it are in phase (a phase shifter can be used); (ii) the coupling to the ring should be variable to compensate for losses in the ring and control the magnitude of the wave travelling along it. Therefore, a variable directional coupler, which consists of two directional couplers and a phase shifter can be used; and (iii) a method to match out any backward wave should be provided. In this case, two waveguide transformers have been used at the input and output of the DUT.



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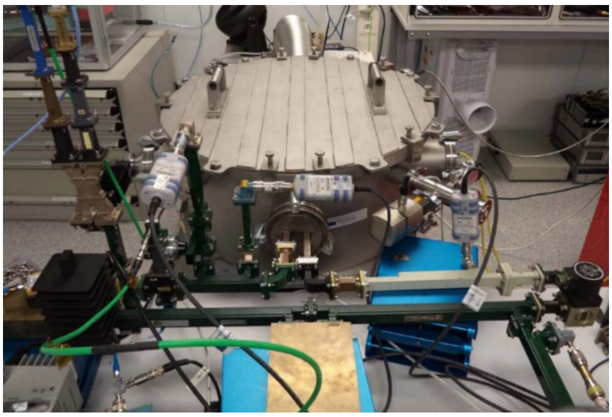

b)

Figure 12. a) Schematic and b) photograph of a multipactor test bed, including a ring resonator (photograph courtesy of the European High Power RF Space Laboratory - European Space Agency (ESA) and Val Space Consortium (VSC)).

Conclusions

In satellite communications, increasing capacity means increasing the bitrate, accommodating a larger number of channels, and, hence, the need for the satellite to handle higher combined signal power. New classes of high-power filters are in the spotlight of both the academia and industry, and some proposals have been developed for increasing power handling. Multipaction is the main high-power phenomenon associated with high-power RF satellite payloads. Multi-frequency and multibeam satellites complicate design, simulation, and testing. Thermal control is another challenge that engineers of high-power payloads have to face. New aluminum alloys with lower coefficients of thermal expansion may help, especially if parts can be additively manufactured and silver plated. The relationship between additive manufacturing and high power is an unexplored topic where more research is needed, as well as the development of specific space-oriented materials that can provide better heat dissipation.

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References

[1] D. Psychogiou and R. Gómez-García, "Symmetrical quasi-reflectionless SAW-based bandpass filters with tunable bandwidth," *IEEE Microwave and Wireless Components Letters*, vol. 29, no. 7, pp. 447-449, July 2019.

[2] J. Hong and M. J. Lancaster, "Aperture-coupled microstrip open-loop resonators and their applications to the design of novel microstrip bandpass filters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, no. 9, pp. 1848–1855, September 1999.

[3] Y. Wang and M. Yu, "True inline cross-coupled coaxial cavity filters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, no. 12, pp. 2958–2965, December 2009.

[4] S. Bastioli and R. V. Snyder, "Inline pseudoelliptic $TE_{01\delta}$-mode dielectric resonator filters using multiple evanescent modes to selectively bypass orthogonal resonators," *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 12, pp. 3988–4001, December 2012.

[5] V. E. Boria and B. Gimeno, "Waveguide filters for satellites," *IEEE Microwave Magazine*, vol. 8, no. 5, pp. 60-70, October 2007.

[6] R. V. Snyder, A. Mortazawi, I. Hunter, S. Bastioli, G. Macchiarella, and K. Wu, “Present and future trends in filters and multiplexers,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 10, pp. 3324–3360, October 2015.

[7] M. Yu, “Power-handling capability for RF filters,” *IEEE Microwave Magazine*, vol. 8, no. 5, pp. 88-97, October 2007.

[8] A. Hatch and H. Williams, “The secondary electron resonance mechanism of low-pressure high-frequency gas breakdown,” *IEEE Journal of Applied Physics*, vol. 25, pp. 417-423, April 1954.

[9] J. Vaughan, “Multipactor,” *IEEE Transactions on Electron Devices*, vol. 35, pp. 1172-1180, July 1988.

[10] W. –C. Tang and C. M. Kudsia, “Multipactor breakdown and passive intermodulation in microwave equipment for satellite applications,” *in Proceedings Military Communications Conference (MILCOM)*, CA, October 1990, pp. 181-187.

[11] R. Levy, “Tapered corrugated waveguide low-pass filters,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 21, no. 8, pp. 526-532, August 1973.

[12] V. E. Boria, P. Soto, and S. Cogollos, “Distributed models for filter synthesis,” *IEEE Microwave Magazine*, vol. 12, no. 6, pp. 87-100, October 2011.

[13] M. Simeoni, S. Cacchione, F. Vanin, J. Molina-Perez, and D. Schmitt, “Automatic dimensional synthesis without optimization for stepped impedace low-pass filters,” *Microwave and Optical Technology Letters*, vol. 44, no. 2, pp. 190–194, 2005.

[14] O. Monerris, P. Soto, S. Cogollos, V. E. Boria, J. Gil, C. Vicente, and B. Gimeno, “Accurate circuit synthesis of low-pass corrugated waveguide filters,” *in Proceedings European Microwave Conference (EuMC 2010)*, Paris, France, October 2010, pp. 1237-1240.

[15] F. Teberio, I. Arnedo, J. M. Percaz, I. Arregui, T. Lopetegi, and M. A. G. Laso, “Accurate design of corrugated waveguide low-pass filters using exclusively closed-form expressions,” *in Proceedings European Microwave Conference (EuMC 2017)*, Nuremberg, Germany, October 2017.

[16] P. Vera Castejón, S. Correas Serrano, F. D. Quesada Pereira, J. Hinojosa, and A. Álvarez Melcón, “A novel low-pass filter based on rounded posts designed by an alternative full-wave analysis technique,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 62, no. 10, pp. 2300-2307, October 2014.

[17] I. Arnedo, J. Gil, N. Ortiz, T. Lopetegi, M. A. G. Laso, M. Sorolla, M. Thum, D. Schmitt, and M. Guglielmi, “Ku-band high-power lowpass filter with spurious rejection,” *Electronics Letters*, vol. 42, no. 25, pp. 1460-1461, December 2006.

[18] I. Arregui, I. Arnedo, A. Lujambio, M. Chudzik, M. A. G. Laso, T. Lopetegi, and M. Sorolla, “Design method for satellite output multiplexer low-pass filters exhibiting spurious-free frequency behavior and high-power operation,” *Microwave and Optical Technology Letters*, vol. 52, no. 8, pp. 1724-1728, August 2010.

[19] I. Arregui, I. Arnedo, A. Lujambio, M. Chudzik, D. Benito, R. Jost, F.-J. Görtz, T. Lopetegi, and M. A. G. Laso, "A compact design of high-power spurious-free low-pass waveguide filter," *IEEE Microwave and Wireless Components Letters*, vol. 20, pp. 595-597, November 2010.

[20] I. Arregui, F. Teberio, I. Arnedo, A. Lujambio, M. Chudzik, D. Benito, R. Jost, F. -J. Görtz, T. Lopetegi, and M. A. G. Laso, "High-power low-pass harmonic waveguide filter with TE_{n0}-mode suppression," *IEEE Microwave and Wireless Components Letters*, vol. 22, no. 7, pp. 339-341, July 2012.

[21] M. B. Manuilov and K. V. Kobrin, "Field theory CAD of waffle-iron filters," *in Proceedings European Microwave Conference (EuMC 1999)*, Munich, Germany, October 1999, pp. 1227-1230.

[22] I. Arregui, F. Teberio, I. Arnedo, A. Lujambio, M. Chudzik, D. Benito, T. Lopetegi, R. Jost, F. -J. Görtz, J. Gil, C. Vicente, B. Gimeno, V. E. Boria, D. Raboso, and M. A. G. Laso, "High-power low-pass harmonic filters with higher-order TE_{n0} and non-TE_{n0} mode suppression: design method and multipactor characterization," *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 12, pp. 4376-4386, December 2013.

[23] R. Levy, "Inhomogeneous stepped-impedance corrugated waveguide low-pass filters," *in Proceedings IEEE MTT-S Digest*, Long Beach, 2005, pp. 123-126.

[24] I. Arregui, F. Teberio, I. Arnedo, A. Lujambio, M. Chudzik, D. Benito, T. Lopetegi, R. Jost, F. –J. Görtz, J. Gil, C. Vicente, B. Gimeno, V. E. Boria, D. Raboso, and M. A. G. Laso, "Multipactor-resistant low-pass harmonic filters with wide-band higher-order mode suppression," *IEEE International Microwave Symposium Digest (IMS 2013)*, Seattle, WA, USA, June 2013.

[25] V. E. Semenov, J. Rasch, E. Rakova, and J. F. Johansson, "General study of multipactor between curved metal surfaces," *IEEE Transactions on Plasma Science*, vol. 42, no. 3, pp. 721-728, March 2014.

[26] I. Arregui, I. Arnedo, T. Lopetegi, M. A. G. Laso, and A. Marcotegui, "Low-pass filter for electromagnetic signals," U. S. Patent 8 680 953, European Patent 2 244 330, January 21, 2008. Assignee: TESAT Spacecom GmbH.

[27] F. De Paolis, R. Goulouev, J. Zheng, and M. Yu, "Cad procedure for high-performance composite corrugated filters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 9, pp. 3216–3224, Sept. 2013.

[28] F. Teberio, I. Arregui, A. Gomez-Torrent, E. Menargues, I. Arnedo, M. Chudzik, M. Zedler, F. -J. Görtz, R. Jost, T. Lopetegi, and M. A. G. Laso, "High-power waveguide low-pass filter with all-higher-order mode suppression over a wide-band for Ka-band satellite applications," *IEEE Microwave and Wireless Components Letters*, vol. 25, no. 8, pp. 511-513, August 2015.

[29] O. A. Peverini, G. Addamo, R. Tascone, G. Virone, P. Cecchini, R. Mizzoni, F. Calignano, E. P. Ambrosio, D. Manfredi, and P. Fino "Enhanced topology of E-plane resonators for high-power satellite applications," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 10, pp. 3361-3373, Oct. 2015.

[30] F. Teberio, I. Arregui, A. Gomez-Torrent, I. Arnedo, M. Chudzik, M. Zedler, F. -J. Görtz, R. Jost, T. Lopetegi, and M. A. G. Laso, "Chirping techniques to maximize the power-handling capability of harmonic waveguide low-pass filters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, pp. 2814-1823, July 2016.

[31] S. B. Cohn, “Direct-coupled-resonator filters,” in *Proceedings of the Institute of Radio Engineers*, vol. 45, no. 2, pp. 187-196, February 1957.

[32] L. Young, “Direct-coupled cavity filters for wide and narrow bandwidths,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 11, no. 3, pp. 162–178, May 1963.

[33] R. Levy, “Theory of direct-coupled-cavity filters,” *IEEE Transactions on Microwave Theory and Techniques*, vol. MTT-15, no. 6, pp. 340–348, June 1967.

[34] J. D. Rhodes, “The generalized direct-coupled cavity linear phase filter,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 18, no. 6, pp. 308–313, February 1970.

[35] F. M. Vanin, D. Schmitt, and R. Levy, “Dimensional synthesis for wide-band waveguide filters and diplexers,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 11, pp. 2488–2495, November 2004.

[36] P. Soto and V. E. Boria, “A versatile prototype for the accurate design of homogeneous and inhomogeneous wide bandwidth direct-coupled-cavity filters,” *in Proceedings IEEE MTT-S International Microwave Symposium Digest*, Fort Worth, TX, June 2004, pp. 451–454.

[37] E. Chojnacki, “Simulation of a multipactor-inhibited waveguide geometry,” *Physical Review Special Topics – Accelerators and Beams,* vol. 3, no. 3000, pp. 32001, March 2000.

[38] J. Hueso, D. Raboso, V. E. Boria, B. Gimeno, and C. Vicente, “Study of the multipactor effect in bandpass wedge-shaped waveguide filters,” *IEEE Transactions on Electron Devices,* vol. 58, no. 9, pp. 3205-3212, September 2011.

[39] A. E. Atia and A. E. Williams, “Narrow-bandpass waveguide filters,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 20, no. 4, pp. 258–265, April 1972.

[40] J. Vague, J. C. Melgarejo, M. Guglielmi, V. E. Boria, S. Anza, C. Vicente, M. R. Moreno, M. Taroncher, B. Gimeno, and D. Raboso, “Mulipactor effect characterization of dielectric materials for space applications,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 8, pp. 3644–3655, August 2018.

[41] E. Doumanis, G. Goussetis, W. Steffe, D. Maiarelli, and S. A. Kosmopoulos, “Helical resonator filters with improved power handling capabilities for space applications,” *IEEE Microwave and Wireless Components Letters*, vol. 20, no. 11, pp. 598–600, November 2010.

[42] K. Shamsaifar, T. Rodriguez, and J. Haas, “High-Power combline diplexer for space,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 5, pp. 1850–1860, May 2013.

[43] S. Moraud, S. Verdeyme, P. Guillon, Y. Latouche, S. Vigneron, and B. Theron, “A new dielectric loaded cavity for high power microwave filtering,” *IEEE International Microwave Symposium Digest (IMS 1996)*, San Francisco, CA, USA, June 1996.

[44] A. Panariello, M. Yu, C. Ernst, “Ku-band high power dielectric resonators filters,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 1, pp. 382–392, January 2013.

[45] M. Morelli, I. Hunter, R. Parry, and V. Postoyalko, "Stop-band improvement of rectangular waveguide filters using different width resonators: selection of resonator widths," *in Proceedings IEEE MTT-S International Microwave Symposium Digest,* Phoenix, AZ, May 2001, pp. 1623-1626.

[46] P. Soto, E. Tarín, V. E. Boria, C. Vicente, J. Gil, and B. Gimeno, "Accurate synthesis and design of wideband and inhomogeneous inductive waveguide filters," *IEEE Transactions on Microwave Theory and Techniques*, vol. 58, no. 8, pp. 2220-2230, August 2010.

[47] W. Hauth, R. Keller, and U. Rosenberg, "The Corrugated-Waveguide Band-Pass Filter - A New Type of Waveguide Filter," in *Proceedings 18th European Microwave Week,* Stockholm, 1988, pp. 945-949.

[48] I. Arregui, F. Teberio, I. Arnedo, J. M. Percaz, A. Gomez-Torrent, M. Chudzik, M. A. G. Laso, and T. Lopetegi, "Resonant quasi-periodic structure for rectangular waveguide technology with wide stopband and band-pass behavior," *Progress In Electromagnetics Research C*, vol. 69, pp. 97-104, November 2016.

[49] C. C. H. Tang, "Nonuniform waveguide high-pass filters with extremely steep cutoff," *IEEE Transactions on Microwave Theory and Techniques*, vol. 12, no. 3, pp. 300–309, May 1964.

[50] F. Teberio, I. Arregui, P. Soto, M. A. G. Laso, V.E. Boria, and M. Guglielmi, "High-performance compact diplexers for Ku/K-band satellite applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 10, pp. 3866-3876, October 2017.

[51] C. Kudsia, R. Cameron, W. –C. Tang, "Innovations in microwave filters and multiplexing networks for communications satellite systems," *IEEE Transactions on Microwave Theory and Techniques*, vol. 40, no. 6, pp. 1133–1149, June 1992.

[52] R. Cameron, C. Kudsia, and R. Mansour, *Microwave Filters for Communication Systems: Fundamentals, Design and Applications*. New York, NY, USA: Wiley, 2007.

[53] R. Cameron and M. Yu, "Design of manifold-coupled multiplexers," *IEEE Microwave Magazine*, vol. 8, no. 5, pp. 46-59, October 2007.

[54] C. Arnold, J. Parlebas, R. Meiser, and T. Zwick, "Fully reconfigurable manifold multiplexer," *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 10, pp. 3885–3891, October 2017.

[55] A. Morini, T. Rozzi, and A. Morelli, "New formulae for the initial design in the optimization of T-junction manifold multiplexers", *in Proceedings IEEE MTT-S International Microwave Symposium Digest,* Denver, CO, June 1997, pp. 1025-1028.

[56] S. Cogollos, P. Soto, V. E. Boria, M. Guglielmi, M. Brumos, B. Gimeno, and D. Raboso, "Efficient design of waveguide manifold multiplexers based on low-order EM distributed models," *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 8, pp. 2540–2549, August 2015.

[57] S. Anza, C. Vicente, J. Gil, M. Mattes, D. Wolk, U. Wochner, V. E. Boria, B. Gimeno, and D. Raboso, "Prediction of multipactor breakdown for multicarrier applications: the quasi-stationary method," *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 7, pp. 2093–2105, July 2012.

[58] A. J. Marrison, R. May, J. D. Sanders, A. D. Dyne, A. D. Rawlins, and J. Petit. "A study of multipaction in multicarrier RF components," ESA/ESTEC, Noordwijk, The Netherlands, Tech. Rep. AEA/TYKB/31761/01/RP/05, January 1997.

[59] X. Wang, J. Shen, J. Wang, Q. Song, Z. Wang, Y. Li, R. Wang, T. Hu, Y. Xia, Q. Sun, X. Yin, W. Cui, H. Zhang, X. Zhang, C. Liu, C. Li, and L. Ran "Monte Carlo analysis of occurrence thresholds of multicarrier multipactor," *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 8, pp. 2734–2748, August 2017.

[60] J. Miller and M. Hoft, "Temperature compensation of resonators using different materials and suitable dimensions," *in Proceedings European Microwave Conference (EuMC 2005)*, Paris, France, October 2005.

[61] B. F. Keats, "Bimetal temperature compensation for waveguide microwave filters," Ph.D. dissertation, University of Waterloo, Canada, 2007.

[62] V. Singh, P. K. Ambati, S. Soni, and K. Karthik, "Enhancing satellite communications," *IEEE Microwave Magazine*, vol. 20, no. 3, pp. 46–63, March 2019.

[63] P. Martín-Iglesias, T. Raadik, F. Teberio, J. Percaz, S. Martín-Iglesias, L. Pambaguian, I. Arnedo, T. Lopetegi, I. Arregui, and M. A. G. Laso, "Evaluation of high performance aluminum for microwave filters," *IEEE International Microwave Symposium Digest (IMS 2019)*, Boston, MA, USA, June 2019.

[64] S. Anza, "Multipactor in multicarrier systems. Theory and prediction," Ph.D. dissertation, Universitat Politècnica de València, Spain, 2013.

[65] "Multipaction design and test," ESTEC Doc. ECSS-E-20-01A, ESA, May 2003.

[66] V. Nistor, L. A. González, L. Aguilera, I. Montero, L. Galán, U. Wochner, and K. Karthik, "Multipactor suppression by micro-structured gold/silver coatings for space applications," *Applied Surface Science*, vol. 315, pp. 445–453, October 2014.

[67] M. Ye, D. Wang and Y. He, "Mechanism of total electron emission yield reduction using a micro-porous surface," *Journal of Applied Physics*, vol. 121, no. 12, March 2017.

[68] I. Montero, L. Olmo, L. Aguilera, M. E. Dávila, U. Wochner, D. Raboso, and P. Martín-Iglesisas, "Low-secondary electron emission field under electron bombardment of microstructured surfaces, looking for multipactor effect suppression," *Journal of Electron Spectroscopy and Related Phenomena*, February 2019. https://doi.org/10.1016/j.elspec.2019.02.001.

[69] P. Martín-Iglesias, I. Montero, F. Tenerio, I. Arregui, J. M. Percaz, T. Lopetegi, I. Arnedo, L. Olano, and M. A. G. Laso, "Enhanced multipactor performance in 3D printed microwave parts," *in Proceedings IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes (IMWS-AMP 2017),* Pavia, Italy, September 2017, pp. 675-678.

[70] A. Woode and J. Petit, "Diagnosis investigations into the multipactor effect, susceptibility zone measurements, and parameters affecting a discharge" European Space Agency, Noordwijk, The Netherlands, ESTEC Working Paper 1556, November 1989.

[71] P. Sarasa, A. González, H. Esteban, P. Mader, K. Tossou, and P. Lepeltier, "Comparative study of the power handling capability of space broadband antenna filters in Ku-band," *in Proceedings 5th ESA International Workshop on Multipactor, Corona and Passive Intermodulation in Space RF Hardware*, Noordwijk, September 12-14, 2005.

[72] I. Arregui, S. Anza, I. Arnedo, C. Vicente, A. Lujambio, J. Gil, M. Chudzik, B. Gimeno, T. Lopetegi, M. A. G. Laso, and V. E. Boria, "Multipactor prediction in novel high-power low-pass filters with wide rejection band," *in Proceedings European Microwave Conference (EuMC 2009)*, Rome, Italy, September 2009, pp. 675-678.

[73] C. Vicente, M. Mattes, D. Wolk, H. L. Hartnagel, J. R. Mosig, and D.Raboso, "FEST3D: A simulation tool for multipactor prediction," *in Proceedings 5th ESA International Workshop on Multipactor, Corona and Passive Intermodulation in Space RF Hardware*, Noordwijk, September 12-14, 2005.

[74] Y. Li, W -Z. Cui, and H- -G. Wang, "Simulation investigation of multipactor in metal components for space application with an improved secondary emission model," *Physics of Plasmas*, vol. 22, no. 5, pp. 46–63, May 2015.

[75] SPARK3D, https://www.3ds.com/products-services/simulia/products/spark3d/

[76] M. Jiménez, B. Gimeno, C. Miquel-Espanya, D. Raboso, S. Anza, C. Vicente, J. Gil, F. Quesada, A. Álvarez, M. Taroncher, M. Reglero, and V. E. Boria, "Analysis of the electromagnetic radiation generated by a multipactor discharge occurring within a microwave passive component," *Journal of Physics D: Applied Physics*, vol. 43, no. 39, September 2010.

[77] M. García-Patrón, M. A. Sanz, C. Cuadrado, M. A. Ruiz del Valle, and J. L. Cerrada, "High power resonant line system for corona and multipactor testing," *in Proceedings 9th ESA International Workshop on Multipactor, Corona and Passive Intermodulation in Space RF Hardware*, Noordwijk, April 5-7, 2017.

[78] S. J. Miller, "The travelling wave resonator and high power microwave testing," *Microwave Journal*, vol. 9, no. 3, pp. 50 68, September 1960.