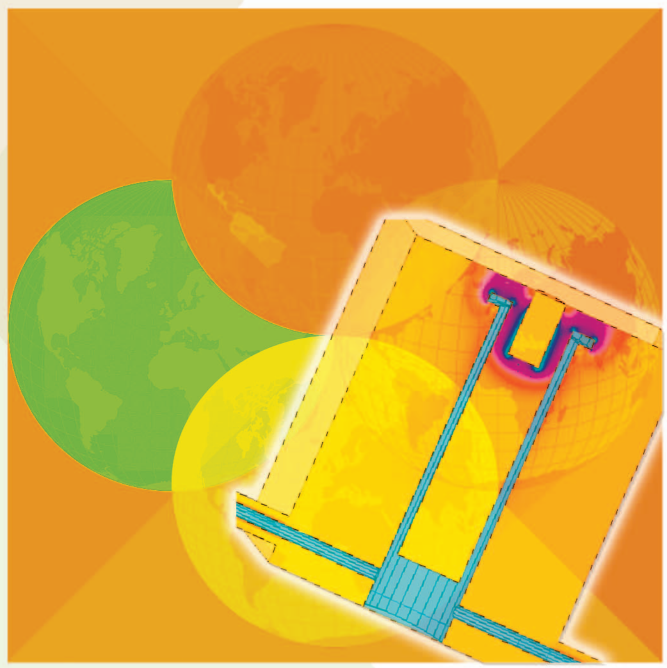
Power-Handling Capability for RF Filters

Ming Yu

Modern high-performance RF (radio frequency + microwave) filters are widely used in communication and radar transmitter systems, where there are demands for the estimation of power-handling capabilities. Since increasing transmitter power levels is the simplest way to boost system range and capability, based on developments in the last decade one can only predict that future systems will require designs with even higher power levels. Typical hardware examples include satellite output filters and multiplexers, wireless or radio base station transmitter filters and diplexers, and transmitter filters in radar systems. Market force also continuously demands volume and mass reduction and presents more and more challenging power requirements. When designing a filter for these high-power operations, one often has to take into account the following effects:



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- multipaction breakdown
- ionization breakdown
- passive intermodulation (PIM) interferences
- thermal-related high-power breakdown and detuning.

Multipaction [1] is an RF vacuum breakdown mechanism in which there is resonant growth of free electron space charge between two surfaces. The intensity of the applied field is such that the electrons bombarding the walls cause continuous release of secondary electrons. Multipaction has occurred not only in RF components designed for operations in space, but in klystrons, cyclotrons, and accelerators.

Ionization breakdown [2] is an RF gas (such as air) breakdown phenomenon where an initially low electron density increases in an avalanche-like manner, thus

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turning an isolating gas into conducting plasma. Ionization breakdown occurs at higher pressures than multipaction. Breakdown must be considered for ground-based and some space-bound components, because RF components designed for operations in space often must be tested on the ground at full power or are required to operate during launch for telemetry purposes.

Multipaction and ionization breakdown are distinct fields of the RF failure mode that have been studied for many years [1]–[2]. In this article, a comprehensive engineering approach to breakdown analysis will be presented with a focus on RF filters. Guidelines for improving peak power-handling capacities will also be covered.

PIM level cannot be predicted accurately for most microwave filters. PIM is largely a workmanship-related issue in production. Techniques for reducing PIM at the design stage [3] are beyond the scope of this article.

Under RF power, RF filters dissipate a significant amount of heat, which leads to an overall temperature rise and local hot spots. In this article, breakdown analysis will be performed for peak power only, while temperature is treated equivalently as an environmental factor. A good thermal engineering design must also ensure an acceptable increase and distribution in the temperature, which is beyond the scope of this article. Other failure modes under high RF power such as detuning, cracking of dielectric resonator or filler material, and added stress can be found in literature [4].

Analyzing the RF breakdown in a filter will include the following steps:

- Determine the breakdown threshold.
- Perform field or circuit analysis to obtain max field or voltage values.
- Compare the worst-case values against the breakdown threshold.
- Determine and apply the safety margins.
- Conduct thermal analysis for extremely high-power devices.

It is desirable in the early design stage that the above process be followed so that the most suitable technology and structure are selected for a given specification. In the following sections, details of the above steps will be presented except for the thermal analysis.

Multipaction Breakdown Susceptibility Threshold

The multipaction effect is a vacuum discharge produced by an RF field between a pair of surfaces. Breakdown in filters is a failure mode that results in noise, harmonics, increased out-gassing, and even eventual gas discharge (when not properly vented). In multipaction breakdown, the pressure is often sufficiently low ($< 10^{-5}$ torr) that the mean free path (average random collision distance of particles) is larger than the conducting surface separation distance (gap). Under an RF field, electrons can travel freely and accelerate to bombard the conducting surface and generate

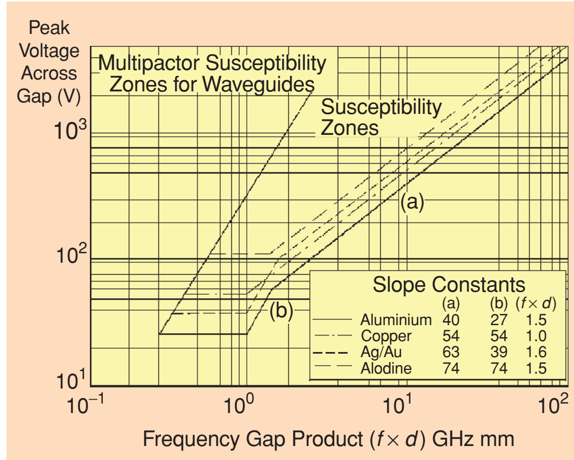

Figure 1. *The susceptibility zone boundaries for different materials.*

secondary electrons. At an odd multiple of one-half cycle, the multipaction (avalanche) effect will occur. Each of these odd numbers is often referred to as the order of multipaction modes. Many researchers have done extensive theoretical and experimental studies to obtain the breakdown threshold as a function of the frequency (f) and gap (size: d) product $f \times d$ (where f is in GHz and d is in mm). Use of this product $f \times d$ allows scaling of the breakdown threshold between results made at different frequencies and with different gap sizes. The data is then used to establish multipaction design curves (susceptibility zones) for the design of high-power RF components.

Waveguide Structure – Parallel Plate Model

The parallel plate model is the most common approach for establishing a multipaction threshold for waveguide structures. It is developed by the European Space Agency (ESA) [1] via a series of experiments with different gap sizes and waveguide geometries. Since vacuum discharge produced by an RF field often requires a pair of surfaces to set up, this model is widely used (at least conservatively) for waveguide filters. In theory, the model is only applied to parallel plate geometry of infinite size, but it is used in many different waveguide structures with different sizes and shapes. It is noted that all ESA tests were done using a reduced-height waveguide section with limited sizes.

The widely used ESA multipaction susceptibility zones [1] for five types of materials are given in Figure 1. Data for each zone boundary, including all modes, is given as:

- Slope $(a) = C(f \times d)$
- Slope $(b) = C(f \times d)^2$
- Change point: $(f \times d)$.

C is the coefficient for slopes a and b, which are listed in Figure 1. Note in region a, a linear relationship exists between product $f \times d$ and the breakdown voltages.

Figure 1 is extremely easy to use because, for most practical filters, silver plating is commonly used and

$f \times d > 1$. Once the frequency (f) and gap (size: d) product $f \times d$ is obtained, simply multiplying it by constant $C = 63$ would result in the maximum peak voltage across the gap. For example, at 10 GHz, a 1-mm gap can take up to a 630 V peak voltage. Figure 1 also points out that when $f \times d < 0.3$ (0.7 in [2]), no multipaction effect will occur.

Multipaction is an RF vacuum breakdown mechanism in which there is resonant growth of free electron space charge between two surfaces.

Coaxial Structure

For a coaxial structure of low impedance (under 50 Ω), the multipaction susceptibility threshold was similar to that of the parallel plate case as shown in the last section. For higher-impedance structures, Woo's curve of NASA in [2] can be used as shown in Figure 2. Although simply increasing the impedance level in a coaxial line will not always result in an improvement in power-handling capability, it is equally wrong to simply analyze a high-impedance structure using the parallel plate model.

In Figure 2, b is the outer diameter and a is the inner diameter. Note that Woo's curve uses root mean square (RMS) value for voltage while the ESA curve in Figure 1 uses peak value. The product $f \times d$ in Woo's curve is in MHz cm. Within $2.3 < b/a < 9.13$, different b/a values can be interpolated from this one.

Summary

In summary, multipaction relies only on secondary electron emission from conducting surfaces. To analyze a real device, voltages across the conducting surface under a specified input power have to be derived from the integration of electrical field components. This will be discussed in the "Obtain Field Strength and Voltage Values" section. Factors like type of gas or pressure level will not impact the breakdown mechanism as long as the pressure is low enough that the mean free path will be larger than the gap between conducting surfaces. Venting is another critical aspect of multipaction analysis that is not covered here [1]. Although the multipaction effect is considered complex, and difficult to predict and test, it is actually one of the more consistent and simpler breakdown mechanisms when compared with ionization breakdown.

Gas Ionization Breakdown Threshold

The most common gas one encounters is, of course, air. The ionization of air (or any other gas, without loss of generality) is caused by electron impacts under an RF field [2], [5]. Contrary to multipaction, the mean free path of air is often much smaller than most physical dimensions (like gaps), which enables a more localized effect. If the energy level (thanks to the RF field) is sufficient to cause ionization of neutral molecules and the total free electrons created by ionization exceed the total loss due to attachment and recombination, the exponential growth of electron density results in electron plasma and eventual breakdown.

The most accurate method for analyzing ionization breakdown involves the kinetic theory and uses a statistical approach and particle distribution equations. The electrodynamic interaction is governed by well-known Maxwell equations. With full boundary conditions applied to complex geometries, extensive numerical modeling is required and is still beyond the reach of most real-life microwave engineers. A semianalytical approximation exists using the variational method [6], [7]. The following equation can be used to calculate the air ionization breakdown threshold (electrical field strength in RMS value, V/cm) as a function of frequency (Hz), pressure (torr), and pulse length (s)

$$E_p = 3.75p\left(1 + \frac{\omega^2}{25 \times 10^{18}}\right)^{\frac{1}{2}} \times \left(\frac{10^6}{p^2 {L_{eff}}^2} + 6.4 \times 10^4 + \frac{20}{p\tau_p}\right)^{\frac{3}{16}}, \quad (1)$$

where

$$p = p_o \frac{273}{273 + T_o},$$

where

p_o: air pressure in torr

T_o: temperature in °C

ω : angular frequency

L_{eff} = effective diffusion length in cm

$\tau\rho$: pulse length in s.

The effective diffusion length L_{eff} [8] can only be derived analytically for limited geometries. For practical purposes, one often approximates it as half of the gap size or simply omits the term (at higher pressure) associated with it in the above equation. Note that at 1 atmosphere pressure (760 torr), one would get an electrical field strength of about 22.8 KV/cm (RMS), which is often used as a rule of thumb within the microwave engineering community. At high altitude H (ft), this formula is often used to convert height to pressure

$$p_o = 758.19 - 28.0924H + 0.3937H^2 - 0.002009H^3. \quad (2)$$

At low pressure, there is more space (larger mean free path) for particles. Eventually, the mean free path is increased to equal the limit d (gap size) where multipaction starts to be susceptible. The mean free path limit separates the ionization and multipaction breakdowns. Generally speaking, reducing pressure leads to lower power-handling capability until it reaches a minimum point, often called the critical pressure. After that, the power-handling capability starts to increase. Figure 3 captures this phenomenon in the so-called Paschen curve [5] with both diffusion length and pulse width as parameters.

One obvious application of Figure 3 is that when a sufficient peak power level cannot be achieved in the test facilities, one may perform an equivalent test at a lower pressure. On the other hand, tests are often required at reduced pressures because operating at elevated altitude is another common request for wireless applications.

Multipaction and ionization breakdown are closely linked phenomena. It is widely believed that the observed multipaction damage may actually be due to a multipaction-induced gas discharge, because ionization is much more energetic and is known to be able to physically damage microwave components such as in leaving burn marks and melting away solder joints. Multipaction damage of this extent is very rare because if the detection system were very sensitive, the test would have been stopped before it had reached such a stage. Multipaction is known to be able to trigger ordinary gas discharges, either by increasing the out-gassing from the component or just by starting breakdown at a very low pressure (such as 10^{-2} torr). At a field strength that is susceptible to multipaction, ionization is not even expected unless out-gassing from multipaction breakdown increases the pressure level at a certain local area. Since gas breakdown can be sustained at a much lower voltage around critical pressure, ionization breakdown occurs as a result of multipaction breakdown. Because the ionization threshold is closely related to the temperature as shown in the above formula, the multipaction threshold is also related to temperature. Another theory is that both multipaction and ionization breakdown happen at the same time at very low pressure (before reaching hard vacuum).

With the established breakdown threshold, it is time to look into field analysis for multipaction (which requires voltage values) and ionization (which requires electrical field strength). The threshold values will be revisited in later sections with more practical considerations.

Obtain Field Strength and Voltage Values

For any homogenous transmission line system such as a waveguide or coaxial line, peak voltages V_o can be easily derived as a function of input power P_o and characteristic impedance Z_o

$$V_o = \sqrt{2 Z_o P_o}.$$

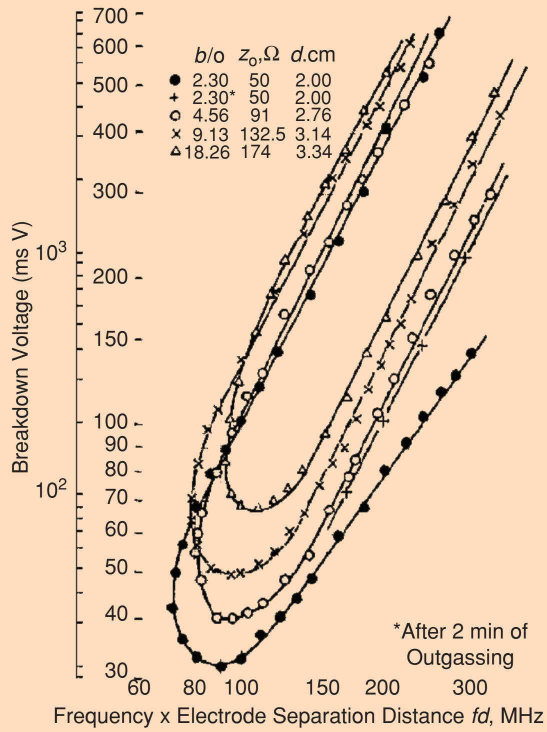

Figure 2. *Multipaction region for coaxial transmission lines with varying values of Z_o.*

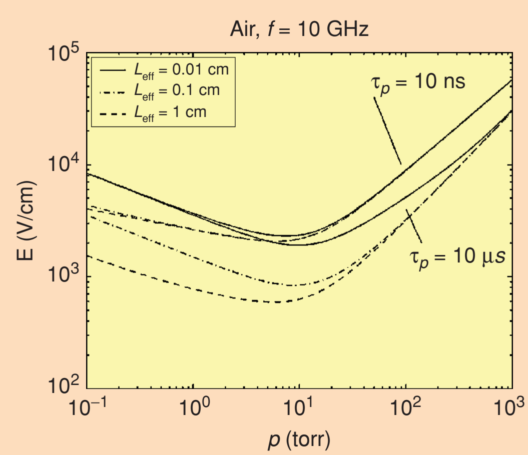

Figure 3. *Paschen curve for pulsed microwave breakdown in air.*

This value is used at an input port as the excitation voltage. Electrical field values are mode dependent and can be derived based on formulas commonly found in microwave engineering textbooks. In most practical cases, high-Q and narrow-band filters are often used. Inside those narrow-band high-Q resonators, electrical field strength or voltages can reach to orders of magnitude higher than input values. This phenomenon is called voltage magnification. For very wideband filters

Ionization breakdown is an RF gas (such as air) breakdown phenomenon where an initially low electron density increases in an avalanche-like manner.

(>20%), the same voltage value as at the input may be directly used inside filters due to low voltage amplification and the extra margins to be discussed in the "Practical Considerations" section.

An exact analysis of the electrical field distribution inside an RF filter involves the three-dimensional (3-D) analysis of the filter structure using either private electromagnetic (EM) codes or commercial tools such as Ansoft HFSS or CST Microwave Studio (MWS). Voltages are simply the results of a line integration of calculated electrical field strength. However, such analyses are possible but extremely time consuming and are even a bit impractical if the filter in question has a very narrow bandwidth, owing to the extreme sensitivity of the filter performance versus dimensions. One often has to waste time to tune the simulated filter response in EM tools to ensure an accurate prediction.

Analyzing a filter's internal voltage using a circuit model was first proposed by Young [12] for inductive iris filters using the Chebyshev prototype. He also suggested the intrinsic connection between stored energy and filter group delay. The works in [13] and [14] verified Young's suggestion by directly establishing the relationship between stored energy and group delay,

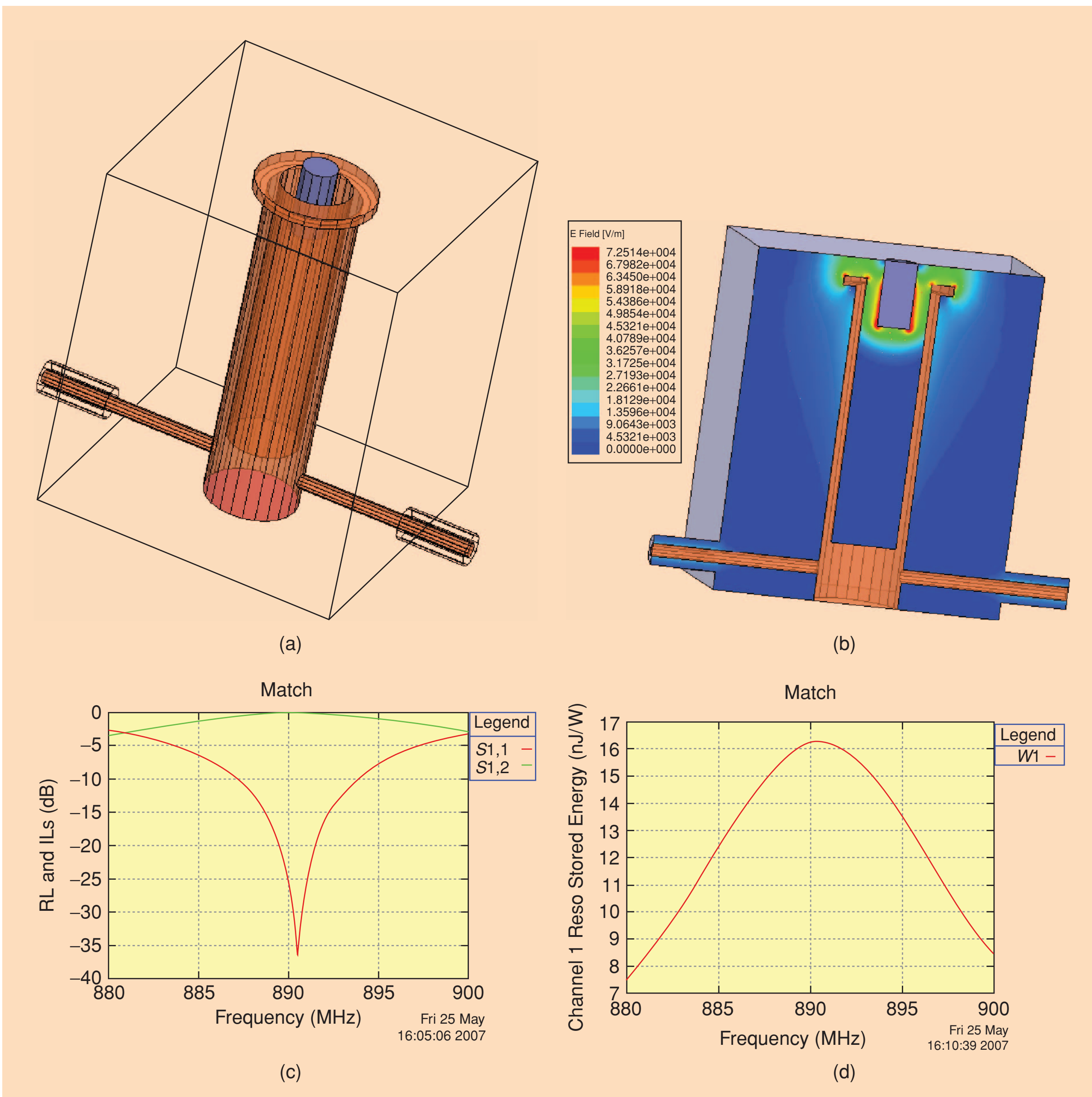

Figure 4. *EM and circuit analysis of a one pole combline filter.*

while [15] proposed general voltage formulation for general cross-coupled filters by using a simple scaling between lumped and distributed circuits. References [16] and [17] introduced scaling from stored energy at a single resonator level. In summary, this process (using electrical field strength as an example) can be summarized as the following:

- Define input power as P_o.
- Use a general multiple coupled circuit model (normalized) to represent a given filter design using source voltage 2 V and source resistor 1 Ω.
- Calculate stored energy for every resonator $W_{c,i}$ (i^{th}). It is most convenient to use units in nJ. The sum of all stored energy will equal the filter group delay (in ns) since the maximum available power is also normalized to 1.
- Create a most representative EM model of a single resonator including all geometrical details. Perform eigen mode analysis and find the maximum electrical field strength or voltages of interest. (Note in HFSS, field values in eigen mode solutions are normalized to 1 V/m, and the internal integration calculator must be used to obtain stored energy. In CST MWS, field strength is more conveniently calculated by normalizing stored energy to 1 J). Normalize field value to stored energy in nJ. E_{em} is then obtained.
- The maximum electrical field strength in the ith resonator for input power P_o can then be scaled to

$$E_{\max,i} = \sqrt{P_o W_{c,i}}\, E_{em}.$$

- Similar to electrical field strength, the internal voltage for the ith resonator is

$$V_{\max,i} = \sqrt{P_o W_{c,i}}\, V_{em}.$$

V_{em} is calculated following exactly the same process above, except an extra line integration of the E field is added. This is the most general approach for analyzing peak field or voltage values by only performing the eigen mode solution for one resonator. Extensive computational effort over a complete filter structure can be avoided. This approach can also be applied to diplexers and even multiplexers to achieve an even greater efficiency improvement.

A simple one-pole coaxial resonator (combline) shown in Figure 4(a) is modeled using both the circuit model (coupling matrix) and the HFSS driven model to demonstrate that a circuit model can predict the stored energy very accurately. The parameters are found in Table 1.

Once EM data is acquired, the circuit model is adjusted to fit the EM model so both have the same s-parameter response as shown in Figure 4(c). The stored energy calculation from the circuit model is 16.25 nJ (the group delay is also 16.25 ns) as shown in Figure 4(d). Using the HFSS internal field calculator to integrate the E field over the whole structure, the stored energy is found to be 16.46 nJ. The difference is less than 1.3%. The E field magnitude is shown in Figure 4(b). This process can be done for multiresonator filters to draw similar conclusions. Since the circuit model gives good representation of the EM model for stored energy, it is used as the base of scaling.

Ionization breakdown occurs at higher pressures than multipaction.

Figure 5 compares the scaled E field strength (at different locations) of the eigen mode solution and a complete driven mode solution for a seven-pole coaxial combline filter.

The results in Figure 5 show that the E field values obtained from these different modeling techniques agree reasonably well. However, complete filter modeling takes an order of magnitude higher amount of CPU time to achieve similar results. Furthermore, single-cavity modeling techniques provide a higher degree of

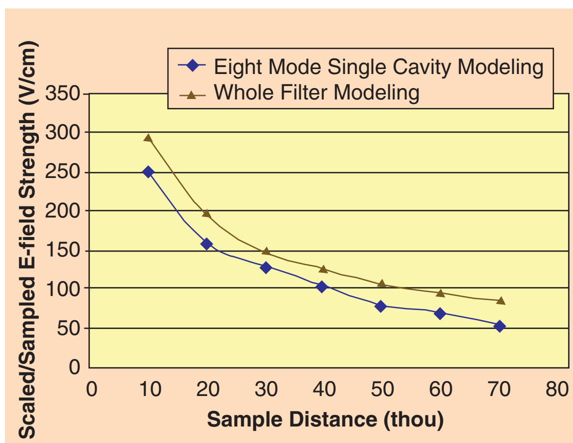

Figure 5. *Scaled E field strength using eigen mode and complete filter approach.*

TABLE 1.

All dimensions in mm	Center frequency: 880.34 MHz
Cavity size: 43 × 43 × 51.92	Bandwidth: 7 MHz
Resonator height: 49, hole depth 40	
Top disk: ϕ17, thickness: 1.5	Coupling matrix
Resonator rod: ϕ 13, inner hole ϕ 10	$R_1 = R_n = 1.399$
Tuning screw: ϕ 5, length: 10	$M_{11} = -0.0464$
I/O coupling tap: ϕ 2, height: 5, outer shell: ϕ 4.6	(Infinite Q is assumed for easy calculation.)

The multipaction effect is a vacuum discharge produced by an RF field between a pair of surfaces.

confidence than whole filter modeling because the meshes on a single cavity model can be refined extensively due to comparably small volume and simplified EM effort.

For most waveguide filters, the voltage estimation procedure based on the lumped-element prototype network can be further simplified [15], [18]. No EM modeling is actually required in many cases. Voltages and

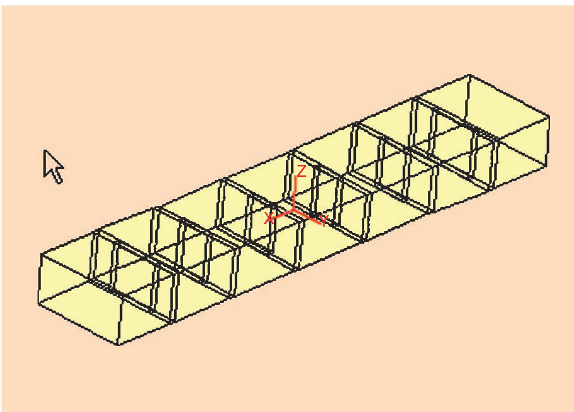

Figure 6. *Five-pole H plane iris filter (WR75 waveguide). Irises: .383, .252, .223, .223, .252, .383; cavities: .523, .589, .597, .589, .523; iris thickness: .050 (all measured in inches).*

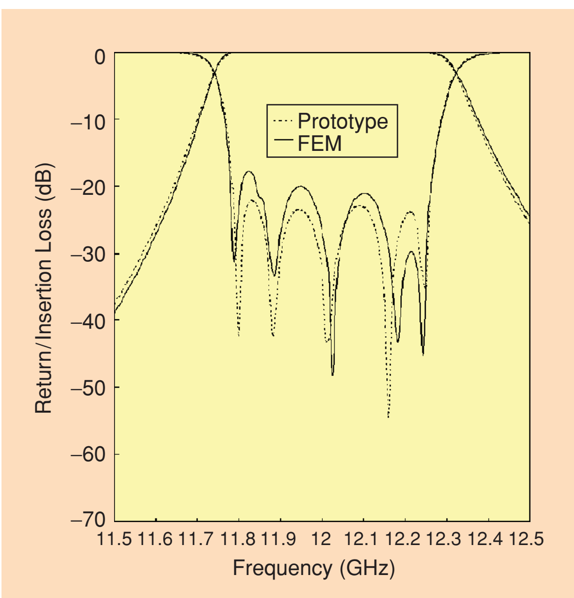

Figure 7. *Five-pole H plane iris filter response using FEM (HFSS) and prototype:* $f_0 = 12026$ *MHz, BW* $= 470$ *MHz, couplings:* $M_{01} = M_{56} = 1.078$, $M_{12} = M_{45} = 0.928$, $M_{23} = M_{34} = 0.662$.

fields are directly obtained from the lumped prototype. In the next example [15], the voltage distribution inside a five-pole H plane iris filter (see Figure 6) with Chebychev response has been computed using the HFSS package. The responses of the filter using the prototype and HFSS (FEM) are compared in Figure 7. The five-resonator voltage distribution was computed as a function of the frequency using the prototype and is plotted in Figure 8. Using HFSS, the voltage corresponding to the E_z component of the electric field (E_z integrated between the broad walls) is computed along the center line of the filter at the band center (12,026 MHz) and at the 3-dB band edge (11,737 MHz) in Figure 9. The peak values in the voltage distribution are compared against the resonator voltages obtained from the prototype. It can be seen that there is a close correlation between the prototype values and the actual peak voltage values from the EM simulation.

In a similar fashion, [18] provided look-up tables for stored energy and simple formulas for the estimation of electrical field strength. No EM simulation is needed. The results were also verified by direct power measurement.

Another application of energy scaling is to design an equivalent test when the desired peak power level cannot be readily achieved. It involves designing a new filter with a smaller bandwidth in order to achieve the same maximum electrical field strength using a lower input power.

Compare the Worst-Case Value Against the Threshold

The results thus far can be summarized as follows:

- If the worst-case electrical strength is greater than ionization breakdown threshold, the device is susceptible to ionization breakdown.
- If the worst-case voltage value is greater than the multipaction threshold, the device is susceptible to multipaction breakdown.

A simple view of those steps is illustrated in Figure 10.

The method presented in this article was extensively validated through testing by the authors of [15]–[18]. Test data will not be presented here.

Practical Considerations

Thus far, a general but simplified approach for analyzing power-handling capability for RF filters has been presented. It was intended to be simple and easy to follow. To perform a practical design analysis, many questions are yet to be answered, such as how much margin is needed. This section is designed to address those concerns.

Equivalent Input Power (Peak)

Electrical field strength and voltage value have been derived for the given input peak power levels. Although in some situations peak power may simply be equal to the average or continuous wave (CW) power P_o specified, peak power level is usually determined based on possible failure modes, modulation schemes, mismatch conditions, and the number of carriers. The peak power value used in the analysis is often raised to an equivalent (higher) value Pe to reflect those practical concerns.

- Mismatch: Raise input peak power level

$$P_e = (1 + |\Gamma|)^2 P_o,$$

  when $\Gamma = -1$ (short circuit), $P_e = 4P_o$.
- Different modulation schemes (or air interfaces) will result in very diverse peak-to-average ratios. Code division multiple access (CDMA) is considered one of the bad cases in that aspect. Often, a CDMA system with only 70 W input power has to be analyzed from $P_e = 700$ to 1,000 W of peak power. Peak-to-average ratio values for different modulation/coding schemes are listed in Table 2 [19].

Multicarrier Operation

In general, the worst-case equivalent peak power P_e for N carriers of equal power P_o is

$$P_e = N^2 P_o.$$

When N is small (up to four), the above formula provides a reasonable worst-case estimation of P_e. When N gets larger, the phase mismatch between N carriers (as they are usually random in nature) will reduce the dwell time of in-phase conditions [20], [21]. When a large number of carriers with different frequencies (even different steps sizes) and amplitudes are added together, the voltage envelope is no longer sinusoidal with constant amplitude. Instead, it depends on the relative phase of each carrier and becomes time dependent. For example, at one point, when the carriers are all in phase, they produce high field/voltage values; at another, when the carriers are all out of phase, they produce values close to zero. This phenomenon severely limits the possibility of the initialization of any breakdown process, because the field amplitude in a multicarrier component will rarely exceed the threshold. Even if the threshold were exceeded, it might not hold long enough to sustain the growth of electron population that would eventually lead to breakdown. For ionization breakdown analysis, one may use either reduced pulse widths together with (1) or apply proper derating from [20]. For multipaction breakdown, a different mode order must be considered in detail [21] together with 20-gap crossing rules (T20) [1]. By using optimization, modes exceeding T20 will be selected and presented with newly reduced multipaction breakdown thresholds.

The parallel plate model is the most common approach for establishing a multipaction threshold for waveguide structures.

TABLE 2. Peak-to-average ratio for different modulation/coding schemes.

Air Interface	Typical Peak to Average Ratio (dB)
AMPS Single Carrier	0
GSM Single Carrier	1.5
TDMA Single Carrier	3.5
IS-95 CDMA Single Carrier	10
WCDMA/UMTS Single Carrier	8-9
IS-95 CDMA Multicarrier	10.5
WCDMA/UMTS Multicarrier	12.2
Edge Multicarrier	9

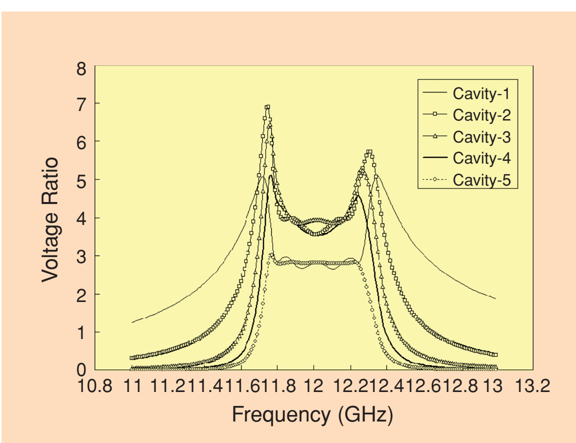

Figure 8. *Resonator voltages (4) as a function of frequency for the five-pole iris filter.*

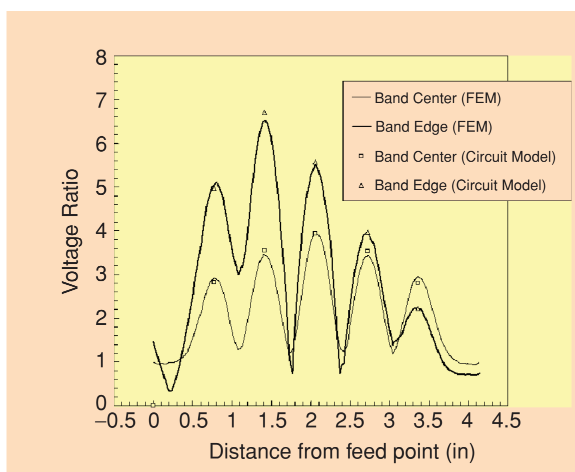

Figure 9. *Voltage distribution along the center line of the filter using FEM and a comparison of the peak values to the values obtained using the prototype method.*

The most accurate method for analyzing ionization breakdown involves the kinetic theory and uses a statistical approach and particle distribution equations.

Sharp Edge

In ionization breakdown analysis, one may encounter numerical problems at sharp edges and even at a rounded corner with a very small radius in a resonator structure. Increasing mesh density of an EM tool often leads to even higher field values and takes a long time to converge. Methods presented in [11] and [22] can be used to deal with this problem. Using 90º sharp edges as the special cases, an equivalent breakdown threshold can be derived at certain distances away from the corner. A simple engineering approach is to sample the electrical field at about 0.1 mm away from the sharp corner (760 torr). This would allow the reuse of the simple process given earlier. In multipaction analysis, voltage values are more mesh friendly because they are derived from the integrations of the electrical field along a predefined line. Other types of edge issues for waveguide irises can be found in [23].

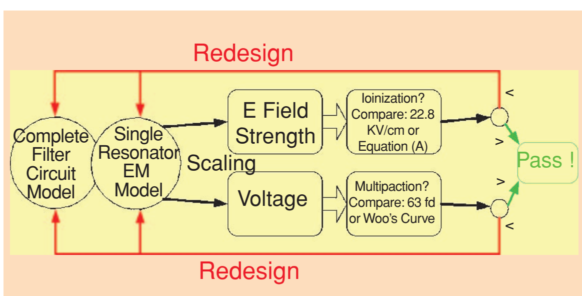

Figure 10. *Simplified approach to predict multipaction and ionization breakdown for a microwave filter.*

Design Margin

Design margin is a controversial issue for designers and end customers. Due to the variability of breakdown, many factors such as workmanship, contaminations, manufacturing tolerances, environmental conditions (temperature, humidity, and pressure), and even test setup come into play. The industry widely accepted design margin ranges from 0 to 6 dB. When a 6-dB margin or above can be demonstrated by analysis, a costly test verification can often be avoided. Pushing a higher margin (even at 6 dB) may drive the hardware cost up exponentially. For obvious competitive reasons, industry often combines analysis, test, and heritage to combat these tricky issues. It should not be a total surprise to hear a filter was shipped with only a 0- to 3-dB analysis margin. It is recommended that engineers and researchers consult the ESA standard [24], which provides a very comprehensive review of multipaction margins.

Typical Design Prevention

Although the focus of this article is the breakdown analysis procedure, typical breakdown prevention methods are briefly discussed since these are needed when the analysis triggers a redesign cycle (unless specified, most prevention methods are equally suitable for reducing the breakdown risk of both multipaction and ionization) [25], [26]. The limitations are identified in brackets.

- Prototype Design Consideration
  - — Use larger bandwidth (when possible) to reduce energy stored in resonators. Avoid operation near the band edge.
  - — Move cross coupling far away from the input port. Avoid designs using asymmetric transmission zeros [13].
- Physical Design Consideration
  - — Use large gap sizes or increase area in order to open up the gap. The goal is to reduce maximum field strength in the gap.
  - — Fill gaps with dielectric material (lower Q).
  - — Avoid sharp edges and use rounded corners.
  - — Use proper venting design.
  - — Use gap size below cutoff (low Q and high sensitivity).
  - — Use no tuning screws (possible for wideband filters).
- External Control (extra components/process, mass)
  - — Employ pressurization at atmosphere or even higher pressure. Use another inert gas such as SF6 or its mix.
  - — Use dc or magnetic biasing to disturb electron trajectory and destroy resonance condition.
  - — Apply a very thin coating that has a low maximum secondary electron emission yield (no practical coating with yield below unity has been found). The other concern is that contamination may change the performance drastically. So far, only black-anodized coating has shown some improvement in feed systems.

Other Factors and Further Reading

Multipaction and ionization breakdown in RF filters are extremely complicated phenomena to analyze, especially when considering the complicated RF signal and environmental factors such as temperature, pressure, and humidity. There is not enough space here to cover detection and test methods, thermal analysis, and venting analysis. This article is intended to present a rather simplistic view of the analysis process to help those who are less familiar with this subject to quickly grasp the concept and obtain results with reasonable accuracy.

Readers are encouraged to consult the references to gain more insight. ESA and NASA documents [1], [2], [24], [25] should be consulted first to gain historic perspectives. The most referenced work from Hatch and Williams [27] is also provided for thoroughness.

Conclusions

A simplified method for evaluating the power-handling capability inside an RF filter has been introduced based on the general cross-coupled prototype network theory, modern EM modeling techniques, and well-established breakdown threshold analysis. The electrical field strength and voltages evaluated using either the single-cavity resonator (eigen mode) model or simply the prototype model have been presented and compared against the direct EM computation of the complete filter structure. Close agreement has been found between the full EM modeling and the scaling of a single resonator or even prototype network analysis only. This procedure is expected to simplify the multipaction and ionization breakdown analysis of filters and filter-based diplexers and multiplexers. The method presented is general and is applicable to all filter types that can be described in a circuit model. Practical issues such as the multicarrier operation, sharp edge condition, design margin, and prevention techniques are also covered.

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As some of the references may be hard to find, the readers may find them at http://ece.uwaterloo.ca/~mingyu