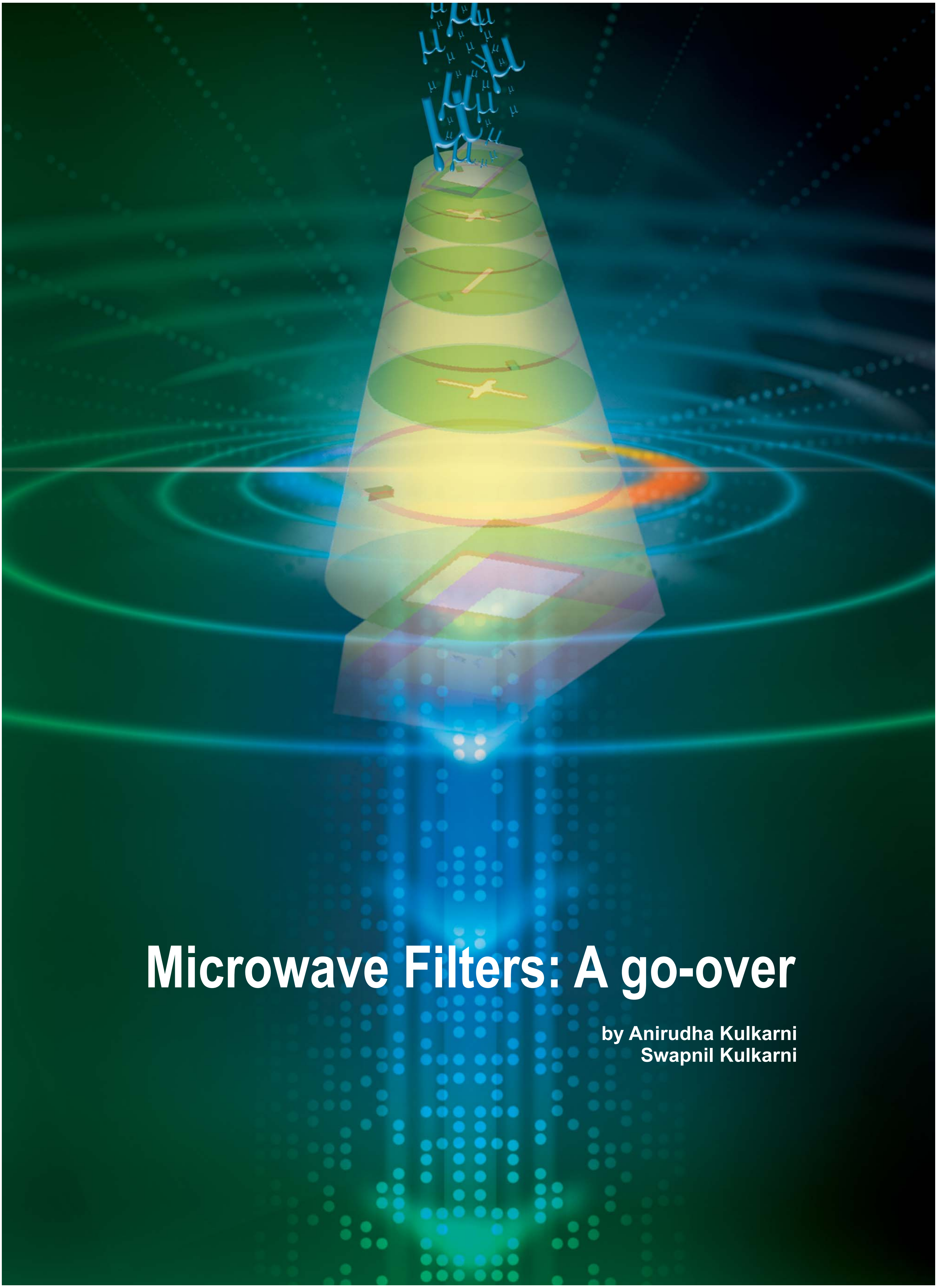

Microwave Filters: A go-over

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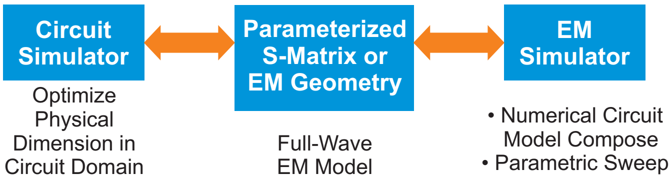
To paraphrase the Bard, “All the world is a filter.” If this wasn't written by Shakespeare, it probably could be attributed to one of the many grizzled veterans of the filter design world.

This definition may certainly be accurate, but it isn't sufficient for microwave engineers. Amplifiers, switches, couplers, mixers, circulators, etc., all suppress (and enhance) waves of certain frequencies, perhaps in preferential directions. Design of practical filters involves consideration of a large variety of disciplines and factors.

Modeling is a vital asset in the design process, but the real properties of filter elements must be incorporated into the modeling process, using an evolutional method in which the model is adjusted to compensate for the unavoidable non ideal nature of the elements, stray couplings, and the like.

The design and development of microwave filters and networks proceeds from strong theoretical underpinnings with readily available theory and software covering such diverse areas as circuit topology, electromagnetic radiation and coupling, thermal and mechanical properties of materials, mechanical resonances, and finish characteristics. Given all of the available theory, it falls upon the developer to properly apply relevant portions of this wide-ranging chest of knowledge, with an artistic touch (the “black magic” aspect of design) and with constant awareness of the situational constraints upon economics that differentiate between science and engineering in the real world.

A wonderful development over the last decade is the artful use of simulation tools to substitute for earlier lab-based cut and try. In a development mode, the designer is usually faced to achieve performance that is just marginally possible. This is because the users of filters and networks are also rather good at simulating what can be done and, consequently, write requirements with almost no margin. It is thus important for designers to be more sophisticated in the use of available tools and to develop ever better models for analysis and prediction.



Transfer function	Frequency Domain Characteristics		Time Domain Characteristics		
	Passband	Stopband	Phase	Group Delay	Pulse Response
Chebyshev	Equal Ripple Flat	Steep	Poor	Poor	Very Poor
Butterworth	Max Smooth	Moderate	Moderate	Moderate	Poor
Gaussian	Max Smooth	Weak	Very Flat	Very Flat	Very Good
Gaussian (6db)	Smooth	Strong	Flat to Moderate	Flat to Moderate	Good to Moderate
Gaussian (12db)	Smooth	Moderate	Flat	Flat	Good
Bessel	Max Smooth	Weak	Very Flat	Very Flat	Very Good

Microwave Filters and Design

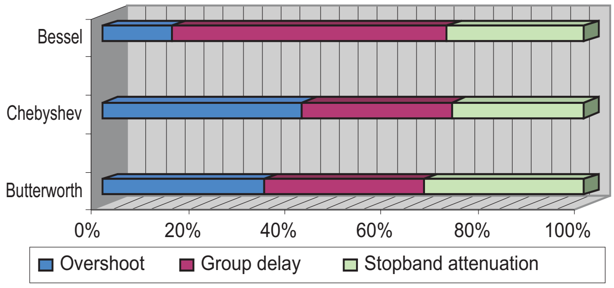
Filter response comparison: It implies the behavior of the filter with respect to steady-state sinusoidal excitation (e.g. energizing the filter with sine voltage or current source and observing its output). There are various approaches to display the frequency response:

- Transfer function (Traditional Approach).
- Attenuation Factor
- S-parameters
- Others, such as ABCD parameters

In case of equiripple or Chebyshev the zeros are usually spaced throughout the passband. This is far more optimum and superior to the maximally flat or Butterworth response, which is rarely used. As far as the poles are concerned, the most common type of filter response has poles located all at dc or infinity and is often described as an all-pole Chebyshev filter, or simply as a Chebyshev filter. When one or more poles are introduced into the stop bands at finite frequencies, the filter is known as a generalized Chebyshev filter or as a pseudo elliptic filter. The special case where the maximum numbers of poles are located at finite frequencies such that the stop bands have equal rejection level is the well-known elliptic function filter.

It should be noted that, at microwave frequencies, lumped realizations of high frequency filters are not usually practical because the wavelength becomes comparable to the physical dimensions of circuit elements. For this reason, a variety of distributed circuit element realizations are used, where one or more of the dimensions of the elements are comparable with the wavelength of operation.

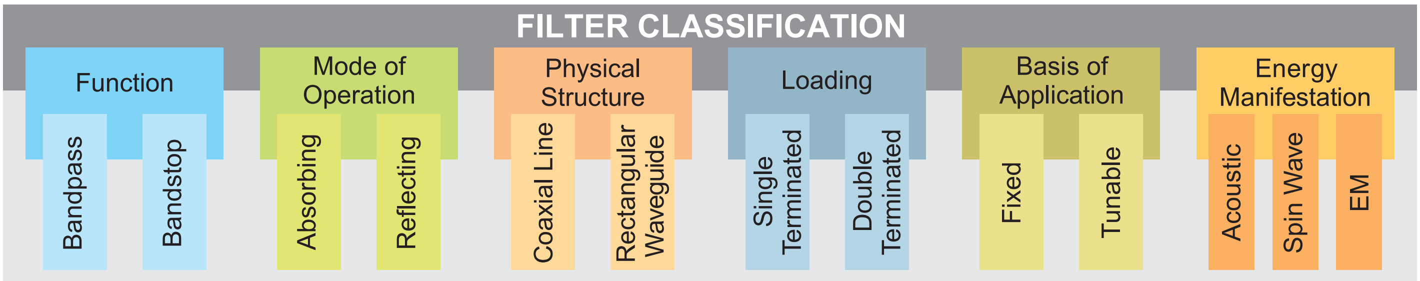
Transfer function vs Characteristics



Dissipation Loss, Group Delay & Power Handling Capacity

The major issue is overcoming dissipation loss. As the number of resonators are increased in order to increase the selectivity, the group delay of a filter increases. Furthermore the group delay of a bandpass filter is inversely proportional to its fractional bandwidth. In addition, the resonators used in a filter have a finite unloaded quality factor,(Q) which depends upon their physical realization.

Now, for a dissipative system, as the group delay is increased, so will the insertion loss. A narrow-band filter will require resonators with a higher insertion loss than a broad-band filter, and will be physically larger if the same type of resonators are used in both cases .The dissipation loss is closely related to the group delay and is nearly proportional to it over most of the pass band. This is intuitively acceptable, since the longer the energy remains inside the filter, the greater should be the amount of its dissipation in the



the filter, the greater should be the amount of its dissipation in the filter.

The power handling capacity is also related to the group delay. The equivalent power ratio is nearly proportional to the ratio of the gross power flow (the sum of the powers in the forward and backward waves) the net power flow (their difference), and is inversely proportional to the power-handling capacity.

Filter Design Methods

Inverse scattering method

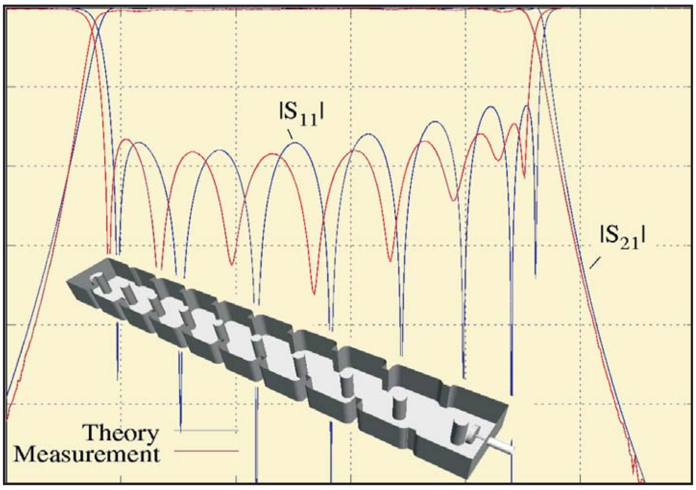
The inverse scattering problem involves reconstruction of the properties of a scatterer, such as shape or density, from knowledge of its scattering data. The scattering data commonly takes the form of the reflection or transmission coefficient of the scatterer, as a function of wavelength. The solution of the inverse problem results in the design of a scatterer which realizes the specified frequency response. Several advantages over other methods, viz: 1) A faithful frequency response over a wide band; 2) No sharp impedance discontinuities; and 3) The ability to realize nonrational transfer functions. In inverse scattering method the governing design equations are in a form that shows the solution for any particular frequency needed to be a linear scaling, in length of the solution obtained for unit frequency.

Insertion Method

The insertion method can be used to characterize a filter response in microwave. It is defined as the ratio of power available from source to power delivered at load. In this program two common types of filter characteristics are used: maximally flat and equal ripple filters.

Some Advanced Application Based Filters

The **rectangular waveguide filter** consists of a uniform section of rectangular guide with post (or other) discontinuities placed across the broad walls of the guide at approximately half-guide-wavelength intervals Usually, the waveguide is operated in its fundamental transverse electric mode (TE_{01}) of operation. Designing this device for wide band operation requires a high value of quality factor (Q). Waveguide filters has a very high value of Q up to 10 000 at 10 GHz are achievable. Secondly, they can handle very high power levels of up to several kilowatts per continuous wave. A disadvantage of using waveguide filters is the relatively large size required for low-frequency operation. The broad-wall dimension of a rectangular waveguide must be considerably greater than one-half of the free space wavelength at cutoff.



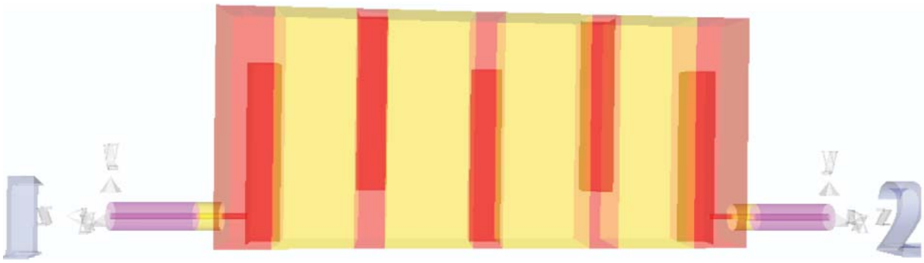
Waveguide Filter with Response

Combline filter are widely used in cellular radio base-stations. It consists of an array of equal length parallel coupled conductors, each of which is short circuited to ground at the same end with capacitive loading on opposite ends. Here, we see that the capacitive loading will drive the resonant frequency of the resonators below that of the series couplings so that relatively strong inter-resonator couplings can occur.

The combline filter has several advantages; 1) It is compact, as the coupled conductors are typically one-eighth wavelength long. 2) The electrically short resonators will not re-resonate until typically six times the center frequency of the filter, giving a broad spurious free stopband, which is not possible with wide-band interdigital filters. 3) It is easier to manufacture than the interdigital filter, as all the tuning screws required for electrical alignment can be on the same face of the filter. Finally, the center frequency of the combline filter may be tuned by an octave or more without causing significant distortion to its frequency.

Interdigital Filters

The prominent application of this filter is at higher microwave frequencies above 8 GHz or so, especially for broad bandwidths. The ideal interdigital filter has characteristics having perfectly arithmetical symmetry, which can be of considerable advantage compared with combline filters. Such symmetry gives better phase and delay characteristics, and it is simpler to design linear. If the coupled line configuration with short-circuit termination of the $\lambda/4$ line is chosen, a useful filter form can be constructed in a rectangular transmission structure. Because the lines are shorted at opposite ends, the structure takes the form of interlaced fingers, and is called an interdigital filter. The casing and fingers typically are silver plated machined aluminum; another form uses cylindrical pins pressed into a housing.

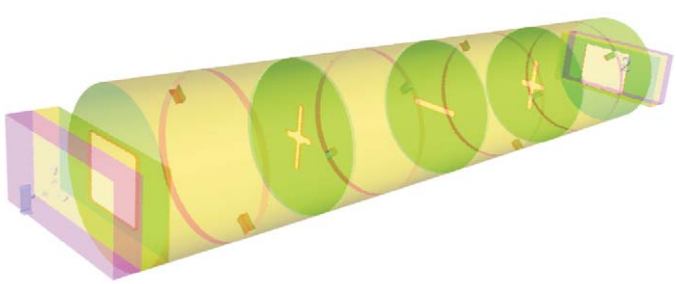


Interdigital Filter

Dual-mode Filter

In 1969, the first longitudinal dual-mode waveguide filter, was developed and later patented realized in circular wave- guides. The basic principle is that a square or circular cavity has spatial symmetry. It can therefore support the dominant mode in either horizontal or vertical directions, thus providing two electrical resonant structures in a single waveguide cavity.

In case of any mode that is not axially symmetrical it allows certain non-adjacent couplings between resonators which could be implemented simply by a cross iris or a coupling screw. This, in turn, allowed incorporation of transfer function zeros along the $j\omega$-axis or real axis or a combination thereof, thus permitting realization of a variety of response functions like elliptic, quazi-elliptic, linear phase etc. Therefore it becomes possible to optimize the channel characteristics and hence the spectral efficiency without any increase in the mass.



Dual Mode Filter

The only drawback, compared to the standard rectangular waveguide filters is that square or circular cavity resonators can support a higher number of spurious modes over wide bandwidths, making the design more complex.

Triple and Quadruple Mode Filters

It was natural for researchers to focus their attention in realizing and controlling more than two modes in a single physical cavity. Comsat Labs was the first to realize a triple-mode filter by using two orthogonal TE_{111} mode and a TM_{010} mode to construct a two cavity six- pole filter. However, use of conventional slot or cruciform type irises for inter-cavity couplings prevented independent control of all the couplings simultaneously.

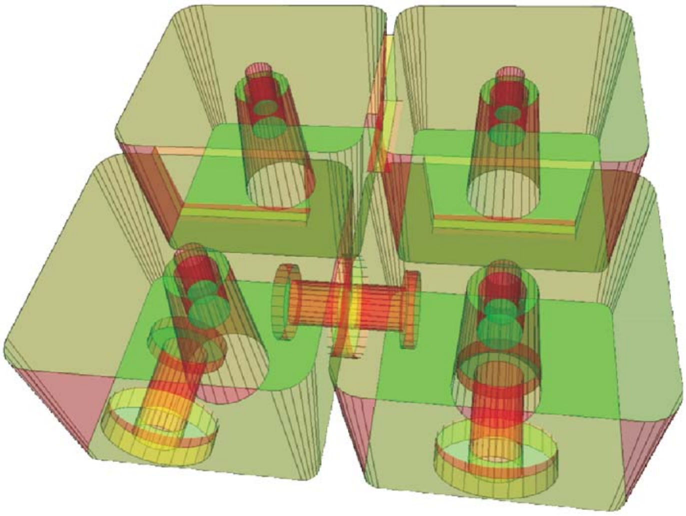
Directional Filters

It can be constructed in waveguide and in strip line. Directional filters can also be realized in a straightforward manner by joining two quadrature hybrids in cascade through a pair of identical filters. For example, in the polarization filter- the two hybrids are two junctions at top and bottom, and the single circular tube represents two waveguides by virtue of which, the two independent circularly polarized waves propagate in it.

Directional filters can be used as channel dropping filters, or as matched diplexers with contiguous channels However, the isolation in one channel will generally not be very good in practice because of the small (but not negligible) reflection in the pass band of the filter pair.

Typical Example of Filter

C-band, V- Sat application based resonator filter incorporating four mushroom post in four cavities, each with capacitive coupling, to facilitate impedance matching of RF in/out cable.



C-Band - Vsat Application Resonator Filter

Available Tuning Strategies and Methods

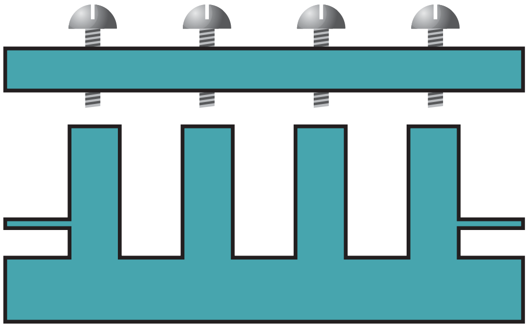
Tuning the filters… "where the rubber meets the road"

The hard part of our work; and where design models are validated.

Tuning Options

Θ Automatic Tuning would be nice, but is very difficult and expensive to setup new jobs every time. However, labour costs are reduced in production and that is very important.

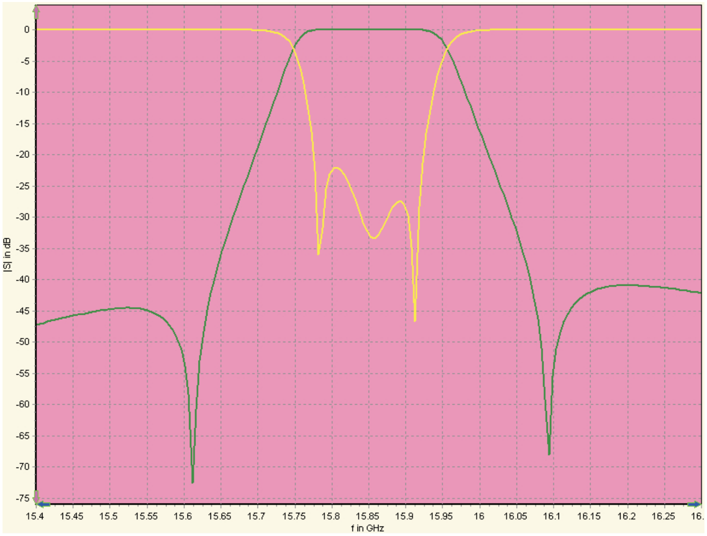
Θ Manual Tuning is labour intensive, requires training and aptitude, but not difficult to setup new jobs. Designs have to be accomplished with consideration to available and selected tuning methods



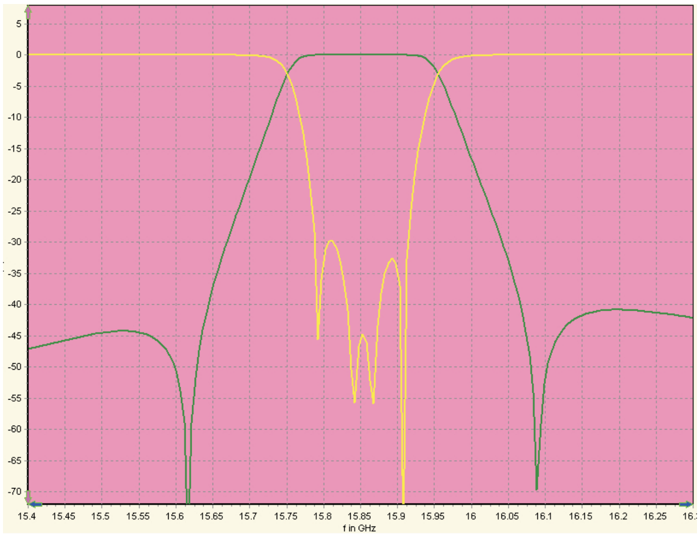
Filter Tunning

For example: A filter tuned by the Dishall method will be very close to the design reflection and passband characteristics. This is a method of tuning multisection filters by observing only the phase of the reflection coefficient at the center frequency of one of the two ports, with the other terminated. Consider a combline filter which has been designed but must now be tuned. If all the tuning screws are shorted to their respective resonators, the output admittance at, say, the input port plane is very high.

As that resonator is tuned, the reflection coefficient stays high because the rest of the filter is still shorted, but the phase of the reflection coefficient can range through a 180°. If we stop at 90° phase angle, we have the correct tuning of the first resonator. Similarly, we can tune the second resonator to another 90° of phase shift, and so on until we come to the last resonator.



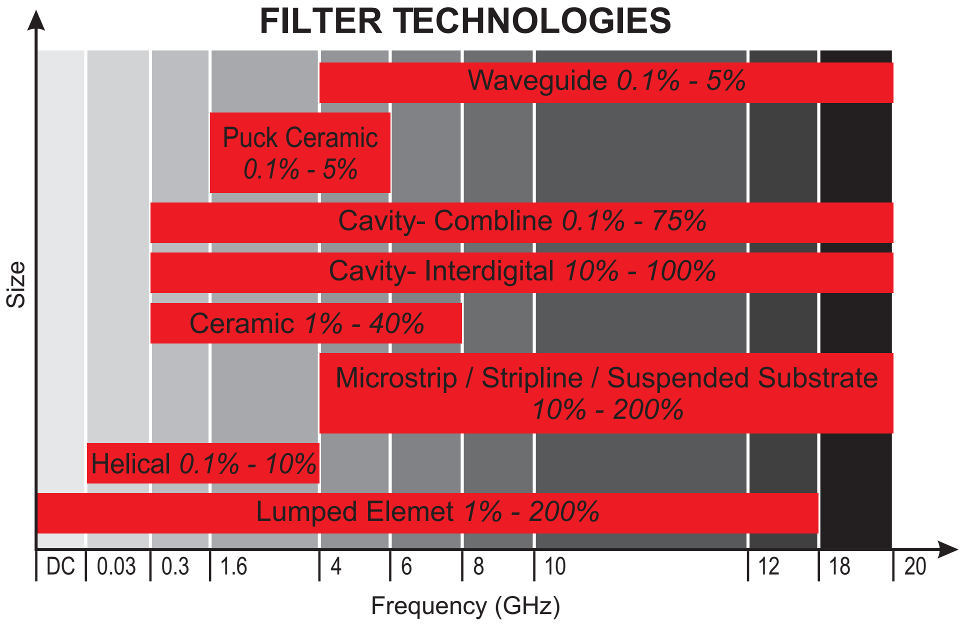
Waffle Filter - Before Tuning



Waffle Filter - After Tuning

This is one of the tricks of the trade that has gone unnoticed for some time.

"Tuning less" is the Holy Grail of filter design, but is elusive in the



real world of manufacturing tolerances and tight specifications.

Filter Synthesis Approaches

Most of the available synthesis techniques are based on models that do not conveniently describe the physical behavior of the filter (e.g., in the case of low-pass prototypes). In recent times, the availability of high-power computational resources has made this approach possible and has lead to the development of computer-aided design (CAD) tools based on different methods, such as the mode-matching method and the space-mapping technique.

Image Parameter Method is more efficient and suitable for simple filter designs, but has the disadvantage that arbitrary frequency response cannot be incorporated into the design.

Insertion Loss Method

A rational polynomial function is used to approximate the ideal $|H(j\omega)|$,$A(\alpha)$ or $|s21|$. Phase information is totally ignored. (There is a historical reason why phase information is ignored. Original filter synthesis methods were developed in the 1920s-60s, for voice communication. Human ear is insensitive to phase distortion, thus only magnitude response (e.g. |H|, A is considered).

Modern filter synthesis can optimize a circuit to meet both magnitude and phase requirements. This is usually done using computer optimization procedures with goal functions.

Optimization: A very important step

It must be applied judiciously. Today, the trend is to exploit optimization techniques and take advantage of the available full-wave electromagnetic (EM) simulators, which can analyze the complete physical structure of many filters. In fact, without a good starting point (i.e., the initially assigned dimensions of the physical structure to be optimized), the most elegant optimization procedure may not be able to find an acceptable solution. For any reasonable number of variables, the EM simulation time is generally prohibitive. It shows one of the ways to mix approximate filter dimensioning (Based on Powell, Gaussian etc.) and optimization allowing a fast and accurate design.

Yield Analysis

The sensitivity of the design to **mechanical or component tolerances** becomes important when considering the potential production delivery rates as well as the cost to produce the filters. We will not be able to wait weeks for solutions nor to afford "doovers" because the designs were flawed. Networks built using quantum wells as resonators are possible (but not yet technologically practical). These present-day shortcomings give us the time to develop the theoretical underpinnings for applications yet to be facilitated by technological improvements.

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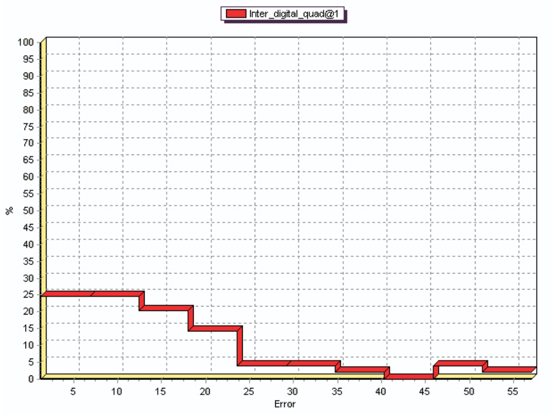

Yield Analysis

Simulation tools have been used to eliminate lab cut and try (multiple prototypes) and squeeze the last gasp of performance out of certain filters. The simulation tools can be applied to mechanical parameters, as well as to fundamental electrical network design.

Conclusion

One of the challenges in wave guide filter is its manufacturability. But rest of the times they do well in entire range of telecom, satellite, radar, microwave heating, avionics etc. Modeling filters at high frequencies realizes the feasibility of combline, interdigital, dual mode, and waffle iron filters, etc.; since microstrip and lumped elements fail to cater the need of good power handling capacity, robustness and better group delays. Besides filter tuning is not easy in case of strip line and lumped filters.

Although the design and development of filter is a vast domain and even an attempt to cover it would be a day dream. The above article is just an honest attempt to cover some of the issues and applications.