

Review of Filter Design Techniques and Power Division for Microwave Frequency

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Abstract—Power dividers and combiners are frequently used in microwave and mm-wave systems such as the feeding network for an antenna array. The major drawback of the conventional Wilkinson power divider is the presence of harmonic bands. Unfortunately, these circuits only offer outputs with unity dividing ratio. Most radio frequency systems use a number of tuned circuits in cascade to achieve the required selectivity (tuning response).

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which the insertion loss or attenuation is to be greater than a prescribed minimum number of decibels. Hence, the performance requirement can be specified by five parameters:

- The Filter Impedance Z_0
- The Passband Maximum Insertion Loss (A_p)
- The Passband Frequency Limit (f_p)
- The Stopband Minimum Attenuation (A_s)
- The Lower Stopband Frequency Limit (W_s)

I. INTRODUCTION

The Most Important Thing To Bear In Mind For Designing Filters Is That Although The Discussion On Filters Starts Off By Describing Low Pass Filters, We Will Show You Later By Examples How Easy It Is To Change A Low Pass Filter Into A High Pass, A Bandpass Or A Bandstop Filter. Figure 1(A) Shows The Transmission Characteristics Of An Ideal Low Pass Filter On A Normalized Frequency Scale, I.E. The Frequency Variable (f) Has Been Divided By The Pass-Band Line Frequency (f_p). Such An Ideal Filter Cannot, Of Course, Be Realised In Practice. For a Practical Filter, Tolerance Limits Have To Be Imposed And It May Be Represented Pictorially As In Figure 1(B).

II. TYPES OF FILTERS

There are many types of filter. The more popular ones are:

- Butterworth or maximally flat filter;
- Tchebyscheff (also known as Chebishev) filter;
- Cauer (or elliptical) filter for steeper attenuation slopes;
- Bessel or maximally flat group delay filter.

All of these filters have advantages and disadvantages and the one usually chosen is the filter type that suits the designer's needs best. You should bear in mind that each of these filter types is also available in low pass, high pass, bandpass and stopband configurations. We will discuss in detail the Butterworth and the Tchebyscheff filters.

A. Butterworth filter

Figure 2 shows the response of the maximally flat, power law or Butterworth type which is used when a fairly flat attenuation in the passband is required. The Butterworth filter achieves the ideal situation only at the ends of the frequency spectrum. At zero frequency the insertion loss is zero, at low frequencies the attenuation increases very gradually, the curve being virtually flat. With increasing frequency the attenuation rises until it reaches the prescribed limit. At the 3 dB frequency there is a point of inflexion, and thereafter the cut-off rate increases to an asymptotic value of $6n$ dB/octave, where n is the number of arms. As the number of arms is increased the approximation to the ideal improves, the passband response becomes flatter and the transition sharper. For instance, for 3, 5 and 7 arms, the 1 dB loss passband frequencies are 0.8, 0.875 and 0.91 respectively of the 3 dB frequency, and the corresponding 40 dB frequencies are 4.6, 2.6 and 1.9 times the 3 dB frequency.

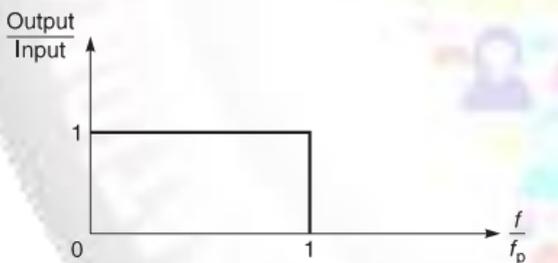


Fig 1(a) Ideal Filter

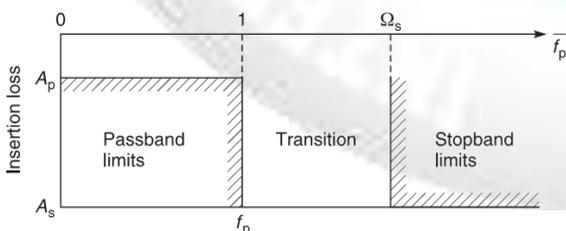


Fig 1(b) Practical filter

The frequency spectrum is divided into three parts, first the passband in which the insertion loss (A_p) is to be less than a prescribed maximum loss up to a prescribed minimum frequency (f_p). The second part is the transition limit of the passband frequency limit f_p and a frequency W_s in which the transition band attenuation must be greater than its design attenuation. The third part is the stopband limit in

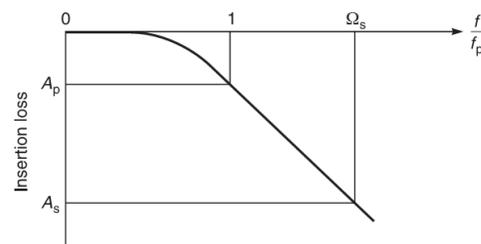


Fig. 2 Butterworth filter

For values of A_s greater than 20 dB and RLR greater than 10 dB, you can use Equation 1 to calculate the number of arms (n) required in the filter for a given attenuation at a given frequency:

$$n = \frac{A_s + \text{RLR}}{[20 \log \Omega_s]} \quad (1)$$

B. Normalized parameters

Each type of filter also has one or more sets of normalized parameters which are used for calculating its component values. Normalized parameters are values which a low pass filter would assume for its components if it was designed for (i) 1 W termination and (ii) an operating angular frequency of 1 rad/s. The reason for choosing 1 W and 1 rad/s is that it enables easy scaling for different filter impedances and operating frequencies. Another point you should note about Figure 5.19 is that the same configuration can be used for a high pass filter by simply interchanging L with C, etc. Bandpass and bandstop filters can also be produced in this manner.

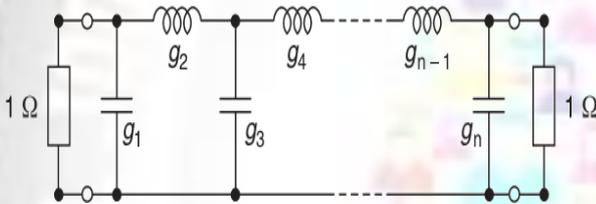


Fig. 3 Schematic of a Butterworth normalized low pass filter
The set of normalized parameters for a Butterworth filter can be calculated from Equation 2:

$$g_k = 2 \sin \left[\frac{(2k - 1)\pi}{2n} \right] \quad (2)$$

where

k = position of element in array [$k = 1, 2, 3, \dots, n - 1, n$]

n = number of elements for the filter

III. LOW PASS FILTER DESIGN

A typical procedure for low pass filter design is given below,

- 1) Decide the passband and stopband frequencies.
- 2) Decide on the stopband attenuation.
- 3) Decide on the type of filter (Butterworth, etc.) you want to use, bearing in mind that some types such as the Butterworth filter give better amplitude characteristics while the Bessel filter gives better group delay.
- 4) Calculate the number of arms you need to achieve your requirements.
- 5) Calculate or use normalized tables to find the values of the filter elements. These normalized values (in farads and henries) are the component values required to make

a low pass filter with an impedance of 1 W and a passband limit frequency (f_p) of one rad/s.

- 6) To make a filter having different impedance, e.g. 50 W, the impedance of each component must be increased by the impedance ratio, i.e. all inductances must be multiplied and all capacitances must be divided by the impedance ratio.
- 7) To make a filter having a higher band limit than the normalized 1 rad/s, divide the value of each component by $(2\pi \text{ times the frequency})$.

Low pass filters can also be designed using transmission lines. We will not do it here because (i) the circuit elements must first be translated into electrical line lengths, and their end capacitances and discontinuities must be calculated, (ii) the effect on the other components must be compensated which means altering line lengths again, and (iii) changing line lengths of each element in turn, then again compensating for the effect of each line length on the other elements. The whole process is rather laborious and is best done by computer design.

IV. HIGH PASS FILTER

A typical procedure for high pass filter design is given below.

- 1) Decide the passband and stopband frequencies.
- 2) Decide on the stopband attenuation.
- 3) Decide on the type of filter (Butterworth, etc.) you want to use, bearing in mind that some types such as the Butterworth filter give better amplitude characteristics while the Bessel filter gives better group delay.
- 4) Calculate the number of arms you need to achieve your requirements.
- 5) Calculate or use normalized tables to find the values of the filter elements. These normalized values (in farads and henries) are the component values required to make a low pass filter with an impedance of 1 W and a passband limit frequency (f_p) of 1 rad/s.
- 6) To calculate the corresponding high pass filter, we must (a) replace each capacitor by an inductor and each inductor by a capacitor and (b) give each component a normalized value equal to the reciprocal of the normalized component it replaces.
- 7) To make a filter having different impedance, e.g. 50 W, the impedance of each component must be increased by the impedance ratio, i.e. all inductances must be multiplied, all capacitances must be divided by the impedance ratio.
- 8) To make a filter having a higher band limit than the normalized 1 rad/s, divide the value of each component by $(2\pi \text{ times the frequency})$.

V. BANDPASS FILTER

For a bandpass filter, the performance must be specified in terms of bandwidth (see Figure 4). The passband limit (f_p) becomes the difference between the upper frequency limit (f_b) and the lower frequency limit (f_a) of the passband, i.e. $f_p = f_b - f_a$. Similarly the frequency variable (f) becomes the frequency difference between any two points on the response curve at the same level: and the stopband limit (f_s) becomes the frequency difference between the two

frequencies (f_x and f_y) outside of which the required minimum stop band attenuation (A_s) is to be achieved.

The response curve will have geometric symmetry about the centre frequency (f_0) This means that the cut-off rate in dB/Hz will be greater on the low frequency side and usually the number of arms required in the filter will be dependent on the cut-off rate of the high frequency side.

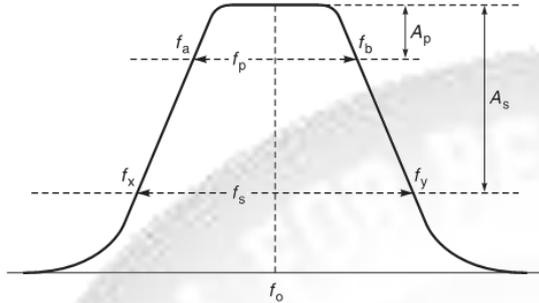


Fig. 4 Bandpass Characteristics

To evaluate a bandpass filter having a passband from f_a to f_b :

- 1 define the pass bandwidth $f_p = f_b - f_a$;
- 2 calculate the geometric centre frequency
- 3 evaluate as previously the lowpass filter having its passband limit frequency equal to f_p ;
- 4 add in series with each inductance (L) a capacitance of value $(1/\omega^2L)$ and in parallel with each capacitance (C) an inductance of value $(1/\omega^2C)$, i.e. the added component resonates the original component at the band centre frequency f_0 .

VI. BANDSTOP FILTER

For a bandstop filter, the performance must be specified in terms of bandwidth (see Figure 5). The stopband limit (f_p) becomes the difference between the upper frequency limit (f_b) and the lower frequency limit (f_a) of the passband, i.e. $f_p = f_b - f_a$. Similarly the frequency variable (f) becomes the frequency difference between any two points on the response curve at the same level: the stopband limit (f_s) becomes the frequency difference between the two frequencies (f_x and f_y) inside of which the required minimum stopband attenuation (A_s) is to be achieved. The response curve will have geometric symmetry about the centre frequency (f_0). This means that the cut-off rate in dB/Hz will be greater on the low frequency side and usually the number of arms required in the filter will be dependent on the cut-off rate of the high frequency side.

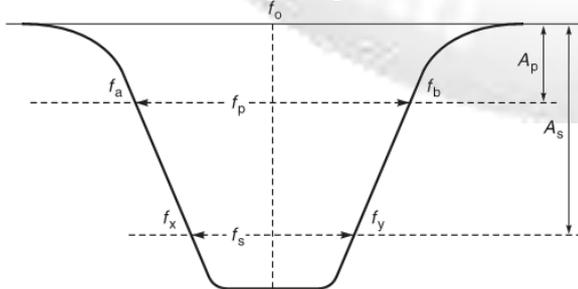


Fig. 5 Bandstop Filter

To evaluate a bandstop filter having a stopband from f_a to f_b :

- 1 define the stop bandwidth $f_p = f_b - f_a$;
- 2 calculate the geometric centre frequency
- 3 evaluate as previously the high pass filter having its stopband limit frequency equal to f_p ;
- 4 add in series with each inductance (L) a capacitance of value $(1/\omega^2L)$ and in parallel with each capacitance (C) an inductance of value $(1/\omega^2C)$, i.e. the added component resonates the original at the band centre f_0 .

VII. TCHEBYSCHIEFF FILTER

Figure 6 shows the response of a filter with a Tchebyscheff or equal ripple type of characteristic. Its response differs from the Butterworth filter in that (i) there is a ripple in the passband response and (ii) the transition region from passband to stopband is more pronounced. In short, the filter 'trades off' passband ripple (A_m) to achieve a greater skirt loss for the same number of filter components. The penalty for using a Tchebyscheff filter is that there is also greater group-delay distortion. The passband approaches the ideal filter at a number of frequencies, between which the insertion loss is allowed to reach the design limit (A_p). This results in a better

approximation and the transition becomes steeper than that of a Butterworth filter with the same number of arms, e.g. for a filter with 0.1 dB passband ripple and having 3, 5 or 7 arms, the 1 dB frequency is 0.86, 0.945 or 0.97 respectively times the 3 dB frequency and the corresponding 40 dB frequency is 3.8, 2.0 or 1.5 times the 3 dB frequency. For $A_s > 20$ dB and $RLR > 10$ dB the number of arms required may be estimated from Figure 6. Note that Tchebyscheff type filters, having an even number of arms, may have different terminal impedances, the ratio of which is a function of A_p , as shown in Figure 6. These filters are sometimes designated by 'b'. Tchebyscheff filters, having an even number of arms and equal terminating impedances, may be designated by 'c'.

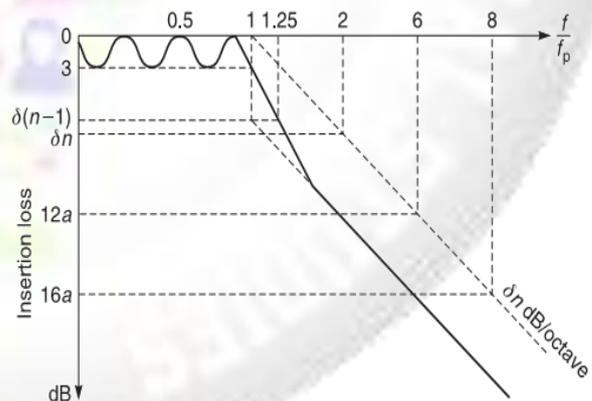


Fig. 6 Tchebyscheff filter response

VIII. CONCLUSION

In the previous sections, we have shown you how to synthesise or design low pass, high pass, bandpass and stopband filters using normalized tables for the Butterworth and Tchebyscheff type filters. We have assumed that the unloaded Q of the elements are relatively high when compared with the loaded Q of the filter. Space limitations prevent us from showing you the synthesis of many other filter types. However, the design procedures are similar.

Many filter designers have produced normalized tables for various types of filters.

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