Picosecond Pulse Labs

# Application Note AN-7a



## Low-Pass Risetime Filters for Time Domain Applications

James R. Andrews, Ph.D., IEEE Fellow

When engineers start working in the Time Domain, they soon learn that the optimum pulse response is the Gaussian (see Figure 1). With the Gaussian waveshape, pulse signals rise and fall smoothly and then rapidly settle to their final values. The presence of other perturbations on a pulse signal, such as precursors, overshoot, and ringing are undesirable. These perturbations extend well beyond the risetime interval and create uncertainty in the actual value of the pulse for a much longer time duration. With the Gaussian, one knows the final value very rapidly after the risetime. The frequency response of a Gaussian system is shown in Figure 2. For a pure Gaussian, the time-frequency relationship is Tr*BW = 0.332, where Tr is the 10%-90% risetime, and BW is the -3 dB bandwidth, $f_o$. For realizable, near-Gaussian response systems, the risetime-bandwidth product is:

Tr(10-90%) * BW (-3dB) = 0.35 **(1)**

For a cascade of several near-Gaussian response systems, the output risetime is the root-sum-of-squares of the individual risetimes as given in equation **(2)**, **[1,2]**.

$$Tr(out) = [\, Tr(1)^2 + Tr(2)^2 + Tr(3)^2 + \ldots + Tr(n)^2 \,]^{1/2} \quad \textbf{(2)}$$

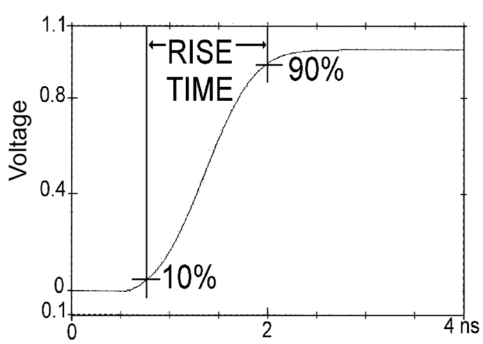


**Figure 1: Step Response of 1 ns Risetime Gaussian**

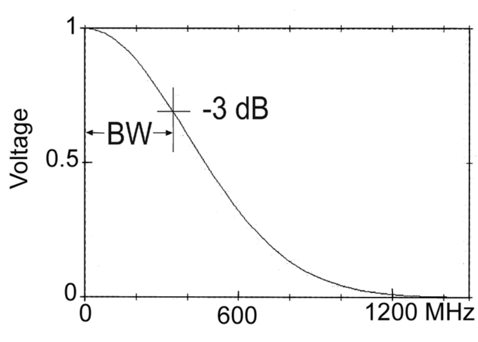


**Figure 2: Frequency Response of 1 ns Risetime Gaussian**

The single most important time domain instrument is the oscilloscope. All oscilloscope manufacturers strive to make their oscilloscopes with responses approximating the Gaussian **[1]**. With the Gaussian, their oscilloscopes come the closest to giving a true measure of the pulse signals under test with the least amount of extra artifacts introduced by the scope. When designing amplifiers and other components for pulse applications, companies such as PSPL also strive to achieve Gaussian responses. When engineers design digital telecommunication systems, they try to obtain Gaussian responses for all the various system components. Maintaining Gaussian responses helps to reduce inter-symbol interference due to early and late perturbations and, as a result, leads to wider opening eye diagrams and lower bit error rates.

There are times when it is necessary to limit the risetime within a pulse system. An example might be a piece of digital telecom equipment that has introduced some additional, undesirable overshoot and high frequency ringing, multiple reflections, and/or high frequency noise on the digital pulse stream. The addition of a low pass filter can help remove some of these defects. In certain digital telecom systems, such as SDH, SONET, and Fiber Channel, system specifications mandate the use of low pass filters with -3 dB cutoff frequencies of 0.75/T and 3.0/T, where 1/T is the Bit Rate.

### GAUSSIAN VS. BUTTERWORTH AND CHEBYSHEV FILTERS

Care must be exercised when selecting a low-pass filter for use in a time domain application. Do not blindly purchase just any low-pass filter that has the desired cut-off frequency. Be particularly careful when purchasing a low-pass filter from the classical RF and microwave component filter manufacturers. They have been making filters for many decades, all aimed towards the frequency domain community that is dealing with relatively narrow-band applications, such as radio communications. For most frequency domain applications, it is very important to have "Brick Wall" type filters. These are filters that pass the in-band desired signals with no attenuation and then completely eliminate any out-of-band signals. For time domain applications, such filters are totally unacceptable. Do not purchase any filters that are advertised as sharp cut-off Chebyshev or Butterworth filters. The Butterworth is sometimes referred to as the "Maximally Flat Amplitude" filter. The Chebyshev is sometimes referred to as "Equi-Ripple" filter.

Why should you avoid Chebyshev or Butterworth filters? Examine Figure 3 for the answer. Here we are showing the step function pulse response of three low-pass filters that all have the same identical -3 dB cut-off frequency, $f_o$, **(*)**. The top trace is a pure, theoretical, 1 ns risetime (10%-90%) Gaussian filter [PG]. Its -3 dB cut-off frequency is 332 MHz, (Tr*BW = 0.332). The middle trace is a 9th order Butterworth filter, [B9], also with a 332 MHz, - 3 dB cut-off frequency. The bottom trace is a 9th order, 0.5 dB ripple, 332 MHz, Chebyshev filter [C9]. The Butterworth and Chebyshev both show extreme cases of 17% overshoot and ringing. The Gaussian has achieved essentially its final value within 2 ns. For the Butterworth and Chebyshev, they require at least 15 ns and 20 ns respectively for their ringing to damp out. In a digital telecom system, either the Butterworth or Chebyshev filter would cause severe intersymbol interference. Even though the Butterworth and Chebyshev filters have the same -3 dB cut-off frequency as the Gaussian, they have longer 10%-90% risetimes. They are 1.48 ns and 1.81 ns, respectively. Their Risetime-Bandwidth products are 0.49 and 0.60, respectively.

The frequency domain responses of these three filters is shown in Figure 4. The Butterworth has the least attenuation and flattest response for frequencies below cut-off. Beyond cut-off, the Butterworth's attenuation is 30 dB down at 1.47 * $f_o$. The Chebyshev filter's equi-ripple response shows 0.5 dB ripple in the passband. Beyond the cut-off, the Chebyshev's response really drops like a rock. Its attenuation is 30 dB at only 1.15 * $f_o$. The Gaussian filter's response is a much smoother, gentler roll-off and is given by equation **(3) [3]**. When equation 3 is rewritten into dB, the very simple relationship of equation (4) results.

$$|H(f)| = \exp[-0.5 * \ln 2 * (f/f_o)^2] \quad \textbf{(3)}$$

$$\text{Atten (dB)} = 3\text{dB} * (f/f_o)^2 \quad \textbf{(4)}$$

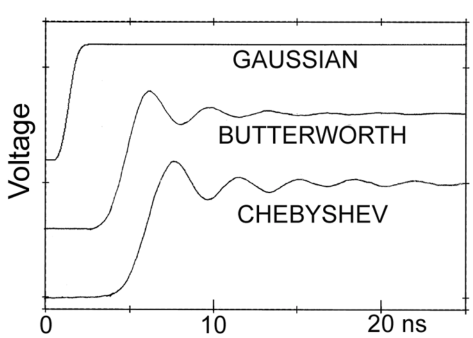


**Figure 3: Comparison of Step Response. $f_o$=332 MHz**

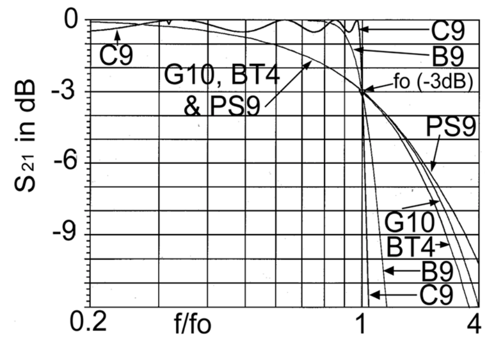


**Figure 4: Comparison of Insertion Loss in dB vs. Normalized Frequency (f/$f_o$)**

The Gaussian filter is 3 dB down at $f_o$, 12 dB down at 2 * $f_o$, and 30 dB down at 3.17 * $f_o$.

**NEAR-GAUSSIAN FILTERS**

The pure, theoretical, Gaussian filter given by equation (3) and shown in Figures 1 and 2 is not actually physically realizable. However, there are several amplifier and filter designs which come close to approximating the pure Gaussian in both the time domain and the frequency domain. A simple R-C low pass filter of several, identical sections rapidly converges with increasing number of sections towards the Gaussian. The most commonly used modern L-C filter designs which approximate the Gaussian are the finite order Gaussian (GN) and the Bessel-Thomson (BT). Some text books refer to the Bessel-Thomson as the "Maximally Flat Delay" filter. References [4 and 5] include design tables for these and many other filter types. Reference [5] includes many curves showing not only the frequency responses, but also the time domain impulse and step responses.

PSPL has developed a unique, proprietary, impedance matched, filter (PS) which will be discussed in further detail in this application note. The actual filters shown and discussed in this note are the pure Gaussian, PG, the 10th order Gaussian, G-10, the 4th order Bessel-Thomson, BT-4, and the 9th order, Z-matched, PSPL proprietary design, PS-9. Figures 4-9 show the frequency responses and time domain step responses of these various filters overlaid onto the pure, ideal Gaussian response.

**(*)** NOTE: All of the frequency domain and time domain results shown in this application note are from computer calculations on idealized circuits. They are not to be considered as guarantees of performance of actual filters. For PSPL products, consult the published specification sheets, and request detailed data on specific bandwidth or risetime filters.

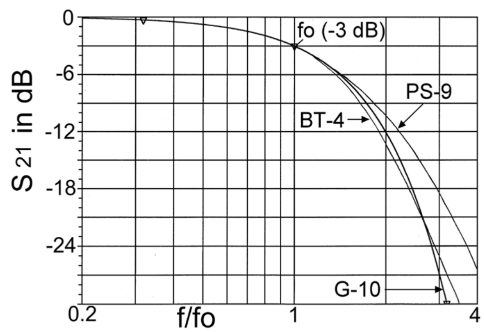


**Figure 5: Insertion Loss in dB vs. f/$f_o$ for Gaussian, Bessel-Thomson and PSPL Low-Pass Filters**

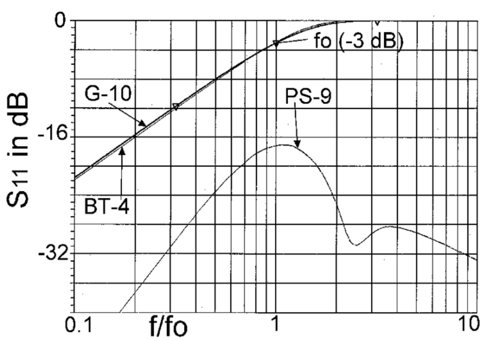


**Figure 6: Retun Loss in dB vs. f/$f_o$ for Gaussian, Bessel-Thomson and PSPL Low-Pass Filters**

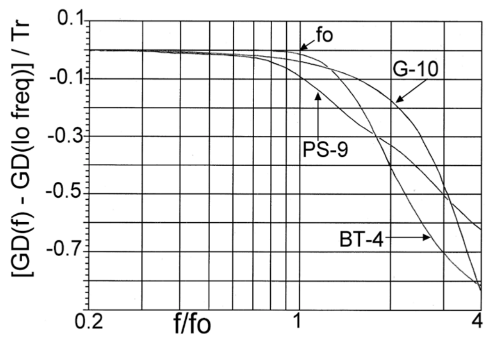


**Figure 7: Group Delay vs. f/$f_o$ for Gaussian, Bessel-Thomson and PSPL Low-Pass Filters.**
Vertical axis is group delay difference normalized to risetime

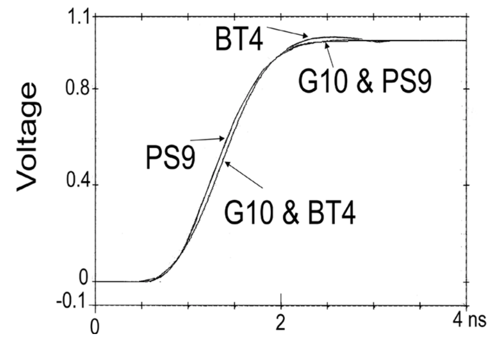


**Figure 8: Time Domain Step Responses of Gaussian, Bessel-Thomson and PSPL Low-Pass Filters. Tr=1 ns**

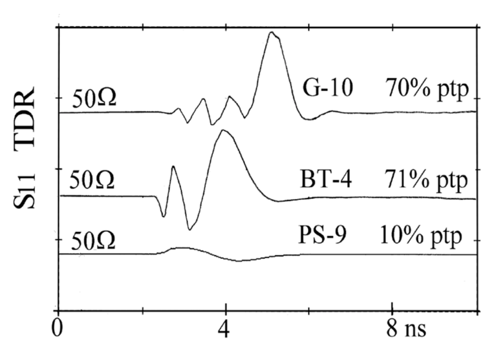


**Figure 9: TDR Signatures of Gaussian, Bessel-Thomson and PSPL Low-Pass Filters**

**Table 1: Time Domain Performance of Near-Gaussian Low-Pass Filters**

| Filter Type | Tr*BW | Overshoot | TDR |
|---|---|---|---|
| Pure Gaussian | 0.332 | None | ---- |
| Gaussian<br>n – 10, G-10 | 0.350 | 0.4% | +59%<br>-11% |
| Bessel-Thompson<br>n = 4, BT-4 | 0.357 | 1.5% | +47%<br>-24% |
| PSPL, Z-Match<br>n = 9, PS-9 | 0.347 | 0.5% | +5%<br>-5% |

## FREQUENCY DOMAIN

For the frequency domain plots, they are all normalized to the -3 dB cut-off frequency, $f_o$. The 10th order Gaussian overlays precisely the pure Gaussian for the ranges shown in these plots. The S21 insertion loss curves, Figures 4 and 5, show that both the BT-4 and PS-9 closely match the Gaussian. The S11 return loss curves (Figure 6) show a dramatic difference between the PS-9 and the BT-4 and G-10. The return loss of the BT-4 and G-10 becomes very bad at frequencies of $f_o$ and beyond. It is only 3 dB at $f_o$. In contrast, the return loss of the PS-9 is very good at all frequencies, with the worst case being 17 dB at the cutoff frequency, $f_o$. Figure 7 shows the normalized Group Delay vs. normalized frequency. The group delay is normalized to the filter's 10%-90% risetime, Tr. The BT-4 shows a flatter group delay than the Gaussian out to $f_o$. Beyond $f_o$, the BT-4's group delay starts changing more rapidly than the Gaussian. The PS-9 closely follows the Gaussian out to $0.7*f_o$, then starts dropping a bit faster. When the frequency reaches $3*f_o$, the PS-9 matches the Gaussian and then changes slower.

## TIME DOMAIN

For the time domain plots, Figures 8 and 9, each filter was designed to have a 1 ns 10%-90% risetime. Figure 8 shows the leading edge risetime of the step responses. All of the responses were adjusted to overlay at the 10% and 90% points. All of the filters had very similar step responses. The G-10 exactly overlaid the pure Gaussian. The BT-4 matched the Gaussian up to the 90% level and then continued to rise faster with a 1.5% overshoot. The PS-9 closely matched the Gaussian below 10% and above 90%. In the 10%-90% region it rose a bit faster. It had a very low 0.5% overshoot. The risetime-bandwidth products for all of these filters are slightly different, but close to the nominal 0.35. See Table 1. Figure 9 shows the input impedance, Time Domain Reflectometry (TDR) signatures of these three filters. Both the G-10 and BT-4 show very poor TDRs, with excessively high reflections reaching as high as +59%. It should be noted that the TDR signatures of the G-10 and BT-4 output ports are drastically different, but also very large. In contrast, the PS-9 shows a very small TDR of only ±5%. This correlates with the good return loss seen in Figure 6 for the PS-9. The excellent return loss and TDR is the significant advantage of the PS-9 over the G-10 and BT-4.

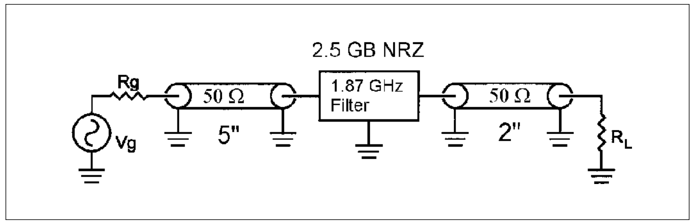


**Figure 10: Performance in a Mismatched Data System**

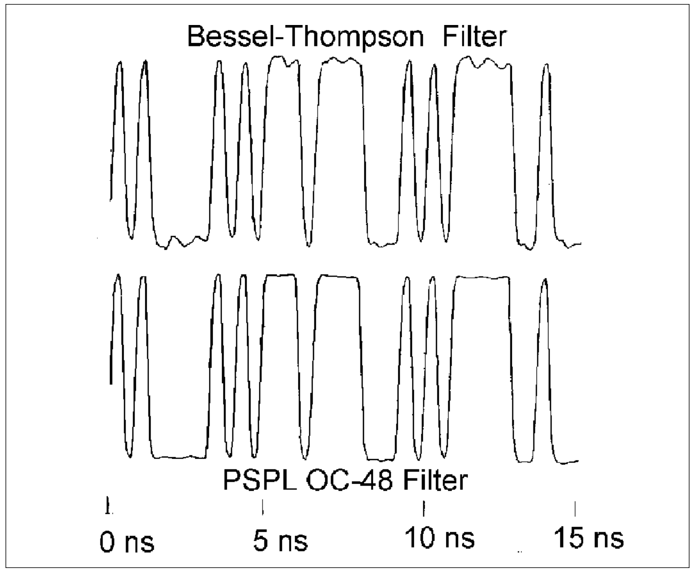


**Figure 11: Performance in a Mismatched Data System. A Randomly Selected 15 ns Segment of 2.5 Gb/s PSRB Data.**

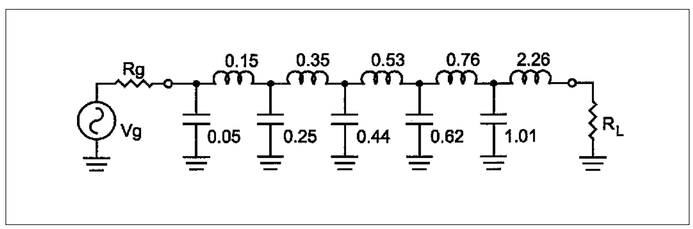


**Figure 12: 10th Order Gaussian Filter**

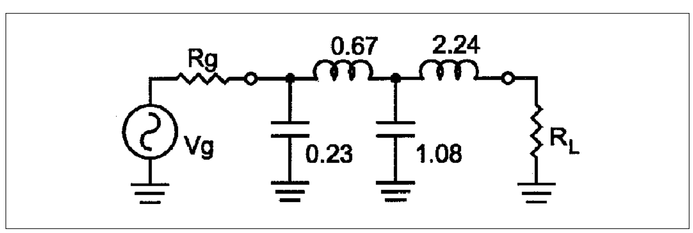


**Figure 13: 4th Order Bessel-Thomson Filter**

## DATA DOMAIN

In this section we will show how the performance of a data system with a low-pass filter can be degraded by multiple reflections. Figure 10 is the simple circuit used for this example. This consists of an OC-48, 2.5 Gb/s, NRZ, data generator, Vg and Rg driving a load $R_L$ through a pair of short, 50 Ω coaxial cables of lengths 5" and 2". A 1.87 GHz low-pass filter is inserted between the two cables. For this example, both the source and load impedances, Rg and $R_L$, were slightly mismatched from 50 Ohms. Their VSWRs were set to 1.22. Their return losses were thus -20 dB.

Mismatches of this magnitude and similar cable lengths are commonly found in data systems. Two 1.87 GHz filters were tested in this circuit, namely a 4$^{th}$ order Bessel-Thomson, BT-4, and a PSPL, PS-9 design. The computer program SPICE was used to run the simulation of the circuit response. A psuedo-random stream of digital data was generated by the computer, and the simulation was allowed to run for a long time to allow a build-up of multiple reflections. Figure 11 shows the results for a randomly selected 15 ns segment of 2.5 Gb/s PSRB data. When the source and load impedances were perfectly matched, i.e., Rg = $R_L$ = 50 Ohms, then the PSRB data stream was perfect with either filter with near-Gaussian-shaped rise and falltimes and perfectly flat tops. However, when the source and load impedances were mismatched, then the BT-4 filter caused the distorted data waveforms shown in the top trace of Figure 11. The ringing on long strings of “0s” or “1s” is very obvious, and there is also some severe pattern-dependent DC-level shifting noted. These data stream distortions will cause closing of the eye diagram and increased bit error rates. The PSPL PS-9 filter also caused some very minor ringing on long strings of “0s” or “1s”, but was much less severe compared to the Bessel-Thomson, BT-4 filter.

## GAUSSIAN AND BESSEL-THOMSON FILTERS

The finite order Gaussian and Bessel-Thomson filter designs are built using only reactive elements and use a cascade of shunt capacitors and series inductors. See Figures 12 and 13. The order of the filter, n, is determined by the number of reactive elements used in the construction. For example, the 4th order BT-4 filter has two shunt capacitors and two series inductors. Each element has a different value, with the smallest values being near the input and the largest near the output. The values shown on Figures 12 and 13 are "normalized". The element values are "un-normalized" using the desired cut-off frequency and the system impedance. The Gaussian and Bessel-Thomson filters, and also most other filter designs, all filter by "Reflection". This is because they are made of purely reactive elements. Any energy that they do not allow to pass through, they must instead reflect back towards the signal source. This is very evident in the return loss plots of Figure 6.

The 10th order Gaussian filter, Figure 12, is an excellent approximation to the pure, ideal Gaussian. Its attenuation vs. frequency matches the ideal Gaussian down to -30 dB. In the time domain it almost exactly overlays the ideal Gaussian. In practice, however, this filter is very difficult to realize because of the extremely wide range of required element values. Particularly for filters in the upper MHz and GHz range, some of the filter element values become much too small to implement in practice. Other disadvantages of this filter are that it is non-symetrical, has poor return loss, and is difficult to precisely tune.

The 4th order Bessel-Thomson filter, Figure 13, has been popular in the past with digital telecom system designers because it is a very simple filter consisting of only 2 capacitors and 2 inductors. It does not follow the ideal Gaussian as closely as the G-10 design. For intermediate attenuations between 3 dB and 20 dB, its attenuation drops faster than the ideal Gaussian. The disadvantages of this BT-4 filter are that it is also non-symetrical, has poor return loss, and is difficult to precisely tune each of the 4 elements.

## PSPL LOW-PASS FILTERS (*)

The PSPL, proprietary, Z-matched, low-pass filter design contains both reactive L and C elements along with resistive elements. The design is variable in order. The results shown in this application note are for a 9th order filter, PS-9. PSPL filters are perfectly symmetrical. There is no designated input or output port. They perform equally well in either direction. The unique aspect of the PSPL filter design is that the input and output impedances are very well matched to 50 Ω, both within the filter pass band and also in the rejection band above the cutoff frequency. See Figures 6 and 9. Filter designs such as the Gaussian and Bessel-Thomson filter filter by "reflection". In contrast, the PSPL design filters by "absorbtion". This means that any energy that is not transmitted through the filter is internally absorbed in resistive elements.

The previous section on Data Domain vividly showed the improvement in BER performance by having an impedance-matched filter in a data system which has some source or load mismatch. PSPL has received numerous testimonials from pleased customers about the system improvement when they replaced Bessel-Thomson filters with PSPL filters. They reported that they often times had been forced to pad their BT-4 filters with 6 dB attenuators on the input and output to compensate for the extremely poor return losses of the BT-4 filters. When they switched to PSPL filters, they were able to then eliminate these attenuators and as a result were able to improve their system dynamic range by up to 12 dB.

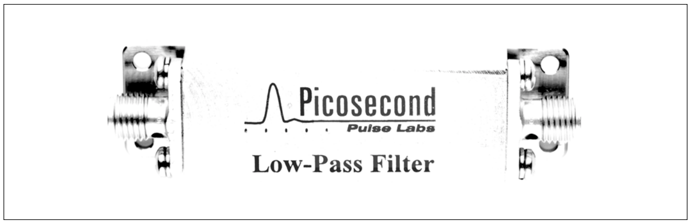


**Figure 14: PSPL Model 5915 Low Pass Filter**

PSPL offers its Z-matched, low-pass filters in several models. The most popular is the Model 5915, Figure 14. The 5915 is stocked for all of the popular SONET, SDH, Fiber Channel, and GigaBit Ethernet data rates from 51 Mb/s to 10 Gb/s. In addition, PSPL will custom-build this filter for any desired -3 dB cut-off frequency ranging from 35 MHz to 15 GHz. PSPL also offers to build filters where the customer instead specifies the desired risetime. For additional details, see the filter specification sheets or call the PSPL application engineers **(*)**.

**REFERENCES**

**[1]** Bob Orwiler, Oscilloscope Vertical Amplifiers, Tektronix, Beaverton, OR, 1969
**[2]** R.D. Thornton et. al., Multistage Transistor Circuits, Chapter 8, "Interrelations Between Frequency Domain, Time Domain, and Circuit Parameters", J. Wiley & Sons, New York, 1965
**[3]** H.J. Blinchikoff & A.I. Zverev, Filtering in the Time and Frequency Domains, Wiley, New York, 1976
**[4]** Reference Data for Engineers: Radio, Electronics, Computer, and Communications, Chp. 9, Ford Shepherd, "Filters, Modern-Network Theory Design", Howard Sams, Indianapolis, 1985
**[5]** A.I. Zverev, Handbook of Filter Synthesis, J. Wiley & Sons, New York, 1967