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Zener Diode Based Integrated Passive Device Filters, An Alternative to Traditional I/O EMI Filter Devices

ON Semiconductor

http://onsemi.com

APPLICATION NOTE

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Background

Electromagnetic Compatibility (EMC) has become a major design concern for all new designs. The designs that are manufactured today must function in close proximity to a wide range of other electronic devices. These devices must be capable of operating without either becoming effected by or adversely effecting the operation of neighboring units. In addition, most systems are connected through input/output (I/O) cables to other systems. Thus the I/O interface has become a major source and entry point for both conducted and radiated Electromagnetic Interference (EMI) and Electrostatic Discharge (ESD).

Today's advanced products are based on integrated devices that are faster and smaller and thus are more noise sensitive than previous generation devices. Designers are being challenged to build more complex units, while reducing the size and cost of the design. In addition, the new designs must be compliant with the revised EMI/ESD standards that are more stringent than previous standards.

Traditional EMI I/O Filter Options

There are several filter design choices available to attenuate the noise entering and exiting an I/O port, including ferrite beads, feed–through capacitors, filter connectors and Pi or Tee filters. These traditional filter devices have been used for a number of years to solve EMI problems; however, these devices tend to be relatively expensive and large in size.

A brief discussion of the different filtering options available to a designer is given in the follow paragraphs. A summary of the advantages and disadvantages of the filter devices is shown in Table 1 on page 2.

Ferrite Beads

Ferrite beads are a series filter device that provides high frequency attenuation with a small resistive power loss at DC and low frequencies. At low frequencies, the device functions as a resistor with a resistance that is typically equal to 50 to 200 ohms. At high frequencies, the device functions as an inductor and has an impedance that increases with frequency. The equivalent model for a ferrite bead is shown in Figure 1. These devices are very effective for solving problems such as the "ringing" noise that often is imposed on high–speed digital signals.

Figure 1. Ferrite bead equivalent circuit

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Table 1. EMI Filter Device Options

EMI Device	Filtering Mechanism	Advantages	Disadvantages	Package Availability
Ferrite Beads	Series attenuation	• Low cost • “Slip–on” package does not require PCB modification	• Relatively large in size • Ferrite material saturates at high DC currents	• Discrete devices • “Slip–on” beads • Integrated package
Feedthrough Capacitors	Shunt attenuation	• Signal is filtered before PCB entry • Small impedance at ground connection • Effective in segmented chassis designs	• High cost • Relatively large in size • Difficult to use on PCB • Tee filter frequency characteristics are dependent on source (cable) and load (receiver) impedances	• Chassis mounting
Filter Connectors	Shunt attenuation	• Signal is filtered before PCB entry • Small impedance at ground connection • Effective in segmented chassis designs	• High cost • Connector size increases	• Chassis mounting
RC Filters	Shunt attenuation	• Current limiting via resistance • Rs are smaller than Ls	• dV/dt limiting, but no voltage clamping for ESD • Filter circuit located on PCB • 1st order LPF with –20 dB/decade attenuation • Rs have insertion loss/power dissipation	• Discrete devices • Integrated package
LC Filters	Shunt attenuation	• 2nd order LPF with –40 dB/decade attenuation • di/dt limiting via inductance • Ls have low insertion loss/power dissipation	• Filter will amplify at self resonance frequency • Filter circuit located on PCB • Ls are bigger than Rs • ESD voltage is not clamped	• Discrete devices • Integrated package
RC Zener Based Filters	Shunt attenuation	• Low cost • Small IC packages • Minimal parasitic inductance • Filter response is “close” to ideal response • Voltage clamping for ESD	• PCB routing complexity increases with multi–channel ICs • Frequency response is not adjustable • 1st order LPF with –20 dB/decade attenuation • Filter circuit located on PCB • Rs have insertion loss/power dissipation	• SMT IC packages • “Flip chips”

The demand of cost sensitive portable products such as cellular telephones has resulted in the development of integrated passive device (IPD) filters that are now available to replace low pass filters that have been implemented with discrete resistors, capacitors and diodes. The NZMM7V0T4 multiple channel filter array, as shown in Figure 2, is the first member of ON Semiconductor's new family of IPD EMI filters that includes single, dual and multiple filter arrays. The schematics for the NZF220TT1 single channel and the NZF220DFT1 dual channel IPD EMI filters are shown in Figures 3 and 4. The zener diode based Pi filters are functionally equivalent to the resistor/capacitor filter shown in Figure 5. The Pi filter circuits are formed by a 100 Ω resistor and two zener diodes that have a junction capacitance of 22 pF.

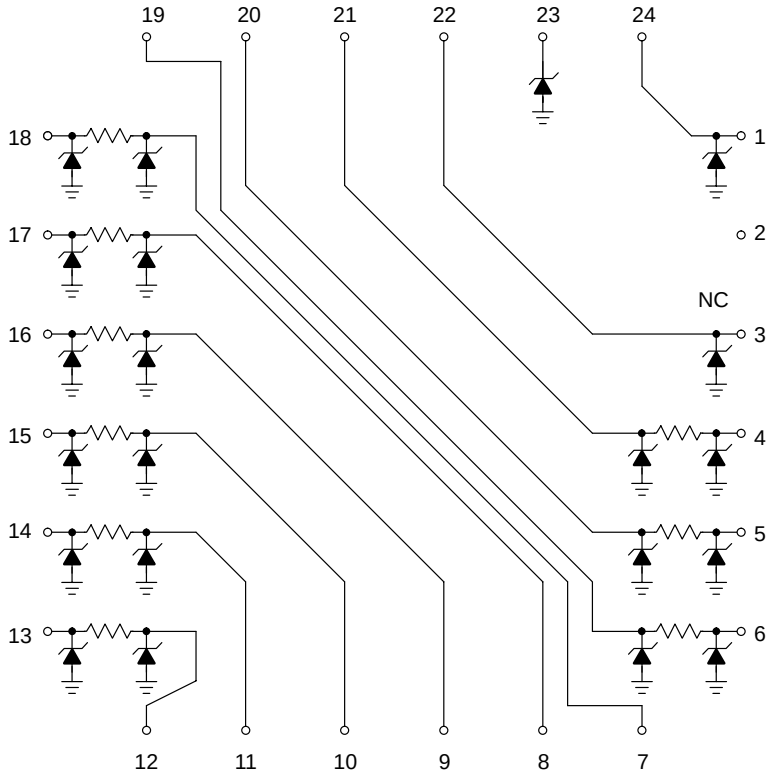

Figure 2. NZMM7V0T4 Device Schematic

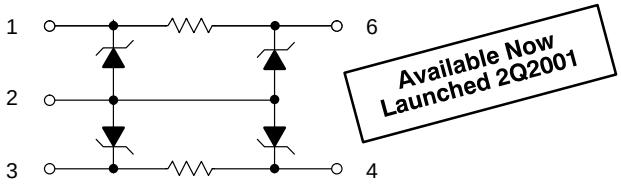

Figure 3. NZF220DFT1 Device Schematic

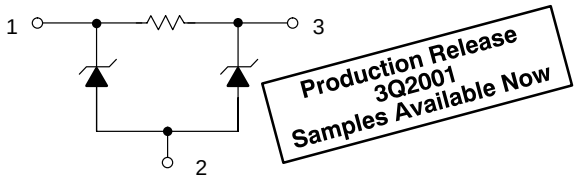

Figure 4. NZF220TT1 Device Schematic

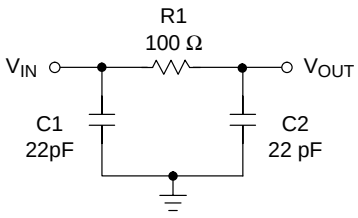

Figure 5. Pi Filter Channel – Equivalent Circuit

Feed–through Capacitors and Filter Connectors

Feed–through capacitors and filter connectors are shunt filter devices that are typically mounted on a conductive chassis or a shielded enclosure. The mechanical mounting forms the ground connection and the high frequency noise is shunted to the chassis ground instead of signal ground. Thus, the noise signal is filtered before the signal reaches the PCB. The effectiveness of the filter is usually very good because the inductance associated with the ground connection is minimized. These devices are very effective for designs that have separate compartments in the enclosure where the filters are used to connect the EMI “clean” and “dirty” segregated portions of the design.

Figure 6 shows the schematic representation of a feed–through capacitor, which is essentially a Tee filter where the resistors and/or inductors are formed by the impedance of the driver circuit and the I/O cable. Filter connectors are available in a number of circuit configurations and the most popular type is a Tee filters made with feed–through capacitors. Figure 7 shows the schematic representation of a feed–through capacitor based filter connector.

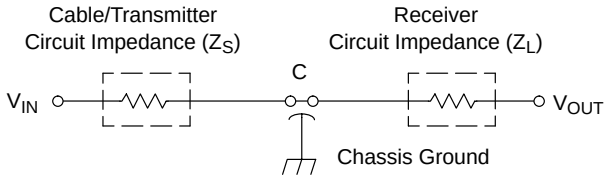

Figure 6. Feed–through Capacitor Equivalent Circuit

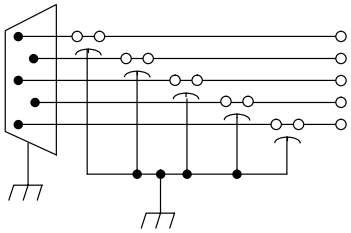

Figure 7. Filter Connector with Feed–through Capacitors

Pi and Tee Filters

The two most popular bi–directional low pass filter configurations are Pi and Tee filters. Pi and Tee filters can be constructed using discrete components, integrated discrete components, or an IPD device that uses zener diodes as the capacitive elements. These filters are typically mounted on a PCB and attenuate the noise to signal ground, in contrast to the enclosure mounted filters that attenuate the noise to chassis ground. Although it is usually more desirable to shunt the noise signal to chassis ground, PCB mounted filters are very effective if the devices can be located in close proximity to the I/O connector.

Pi and Tee filters can be constructed from either LCs or RCs as shown in Figures 8 through 11. These circuits attenuate the noise signals that are both entering and exiting the filter network. In the Pi filter, R1 (L1) and C2 form a filter that attenuates the high frequency signals entering the network via the I/O cable, while R1 (L1) and C1 attenuates the high frequency noise that is exiting the network. In a similar manner, the Tee filter uses R1 (L1) and C1 as a filter to attenuate the incoming signals and R2 (L2) and C1 to attenuate the outgoing signals.

It is necessary to add a transient voltage suppression device such as a zener diode in order to provide ESD protection to the basic Pi or Tee filter. If two zeners are added to the Pi circuit, as shown in Figure 12, the ESD input voltage can be clamped to a non–destructive voltage level that is equal to the zener voltage of the diode. In contrast, a RC or LC filter will only limit the voltage slew rate of the ESD input and will not clamp the ESD voltage.

The LC and RC Pi and Tee filters can be designed to be functionally equivalent as shown in Figure 13; however the LC filters are second order filters with a frequency attenuation roll–off of –40 dB/decade, while the RC filters have a roll–off of –20 dB/decade. The decision to use either a LC or a RC filter is usually based on the amount of power that will be dissipated in the L or R elements. The voltage drop of the resistor in RC filters is often too large for high current circuits; thus a LC filter is the preferred device for applications such as power line filters. For applications such as digital data lines, the voltage drop of the resistance is often insignificant. The insertion loss of the filter is usually not an issue in digital applications and either LC or RC filters can be used because typically the driver circuit output impedance is small (i.e. $Z_S \approx 0$) and the receiver circuit’s input impedance is high (i.e. $Z_L \approx \infty$).

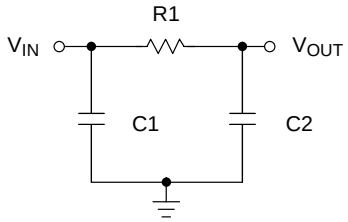

Figure 8. RC Pi Filter

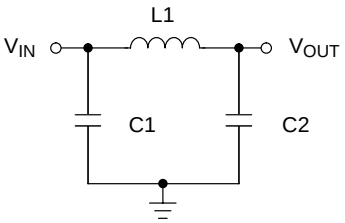

Figure 9. LC Pi Filter

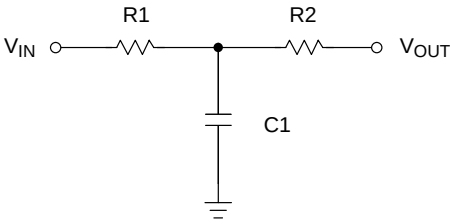

Figure 10. RC Tee Filter

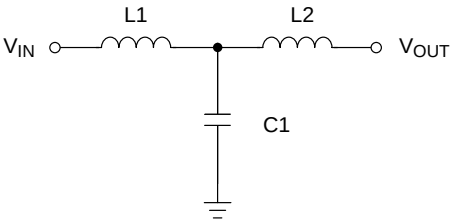

Figure 11. LC Tee Filter

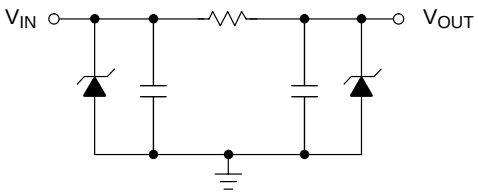

Figure 12. Discrete Pi Filter with ESD Protection

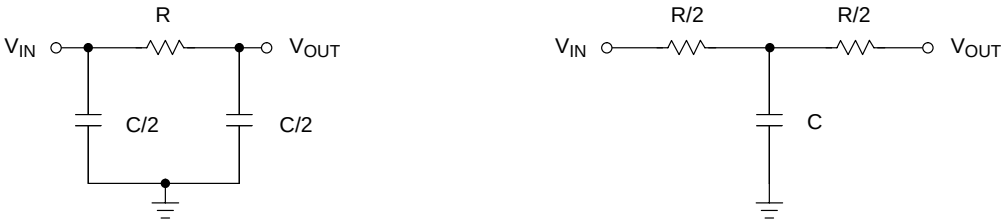

Figure 13. Equivalent RC Pi and Tee Filters

Zener Diode IPD Filters: An Alternative to Traditional EMI I/O Filter Devices

IPD filters are now available in small SMT IC packages to replace the low pass filters that are implemented with discrete resistors, capacitors and zener diodes. These IPD zener diode filters uses the capacitance of a zener diode to form a resistor/capacitor (RC) low pass filter that is typically a Pi filter. IPD filters reduce the component count and the required printed circuit board space. Zener diode IPD filters are available in both Pi and Tee filters and in single line to multiple line filter arrays. In addition, the integration of the filtering network in an IC improves the filter performance by minimizing the parasitic impedances that result from the multiple contacts between the components.

The RC zener based Pi filter is the preferred IC configuration. Inductors are more difficult to manufacture than resistors with standard IC processes; thus RC filters are preferred over LC filters in IPD solutions. Also, a Pi device with two zeners will result in an ESD clamping voltage that is within a few millivolts of the zener breakdown voltage. In contrast, a Tee filter will have a significant overshoot voltage before the zener clamps the ESD pulse to a level that is equal to the zener breakdown voltage. Furthermore, Tee filters have the disadvantage that the input resistor is exposed to the high voltage ESD pulse and high voltage resistors are difficult to implement in silicon. Thus, practical Tee filters typically add two additional zener diodes to the standard Tee configuration as shown in Figure 14.

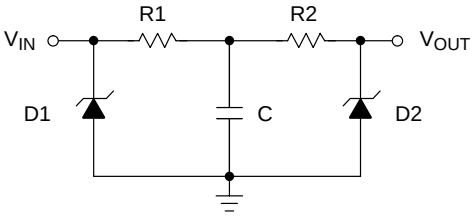

Figure 14. Practical Tee Filter with ESD Protection

Selecting an EMI Filter

A procedure for selecting an EMI filter is shown in Figure 15. This procedure is intended to be a guideline to aid the designer in selecting an effective filter configuration to meet the EMI and ESD design requirements. In addition, this procedure illustrates some of the design issues that need to be analyzed in order to optimize the EMI/ESD solution. This procedure can be used to select any of the various filter devices; however, the examples shown assume that the chosen filter device is an IPD zener diode filter.

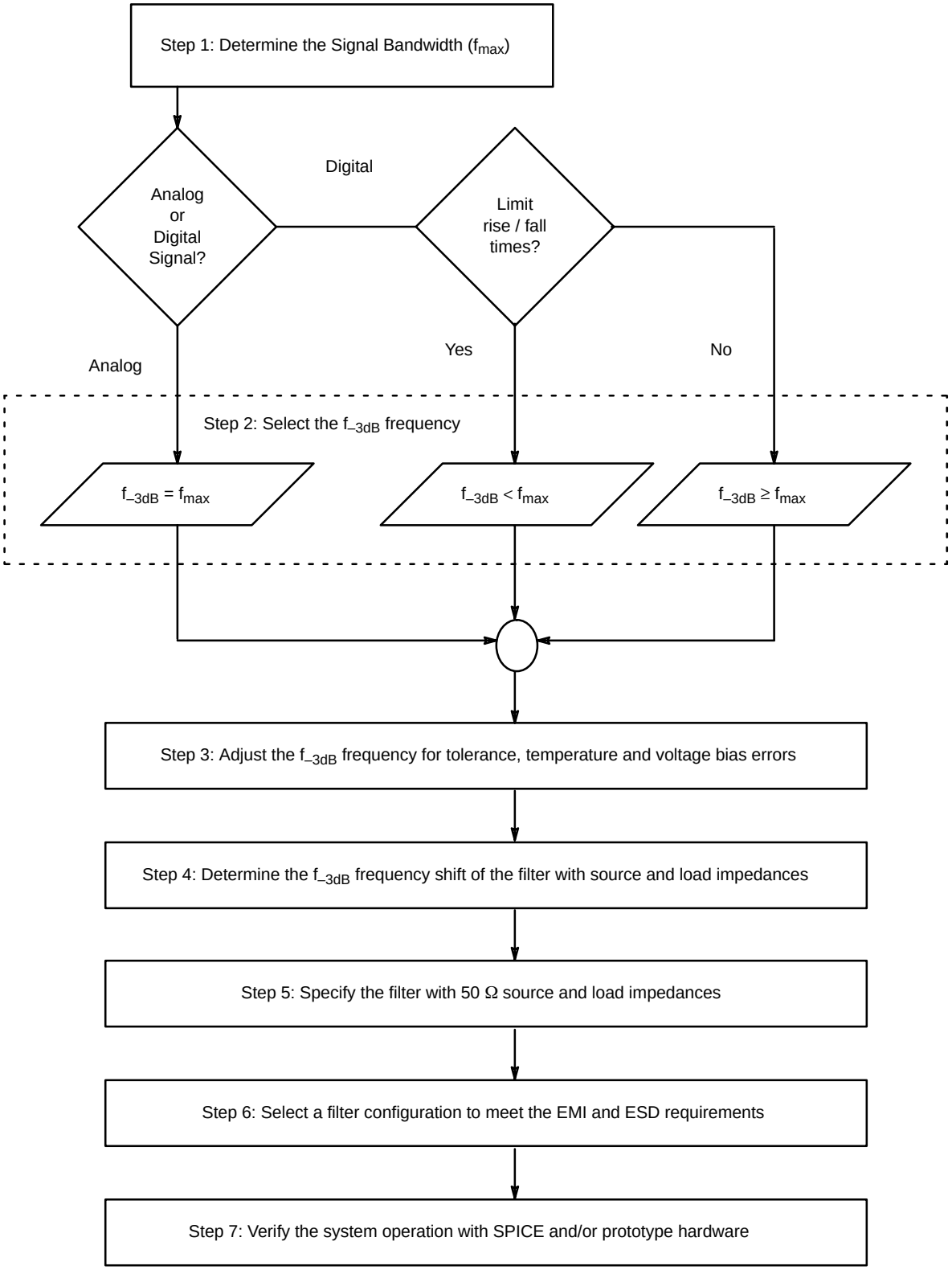

Figure 15. Selecting an EMI filter

In the ideal situation, the designer would have the flexibility to optimize the EMI filter for each channel in a multiple filter channel application. However, in practice the EMI filters are usually chosen to be identical for all of the channels to limit the required components in the design. Therefore, the design procedure typically consists of selecting the filter array's f_{-3dB} frequency to match the requirements of the highest frequency I/O channel. Then an EMI filter device is chosen that provides the desired EMI attenuation and ESD protection characteristics for the I/O signal lines.

Step 1: Determine the signal bandwidth

The frequency spectrum of a signal can be approximated by using a trapezoid to represent the signal waveform. This provides for a quick method that can be used for either analog or digital signals to verify that the EMI filter will not distort the filtered signal. The harmonic content of a periodic trapezoid waveform is determined from the pulse width, duty cycle and the rise time of the waveform, as shown in Figure 16. The definition of the corresponding f_1 and f_2 frequency response poles are listed below:

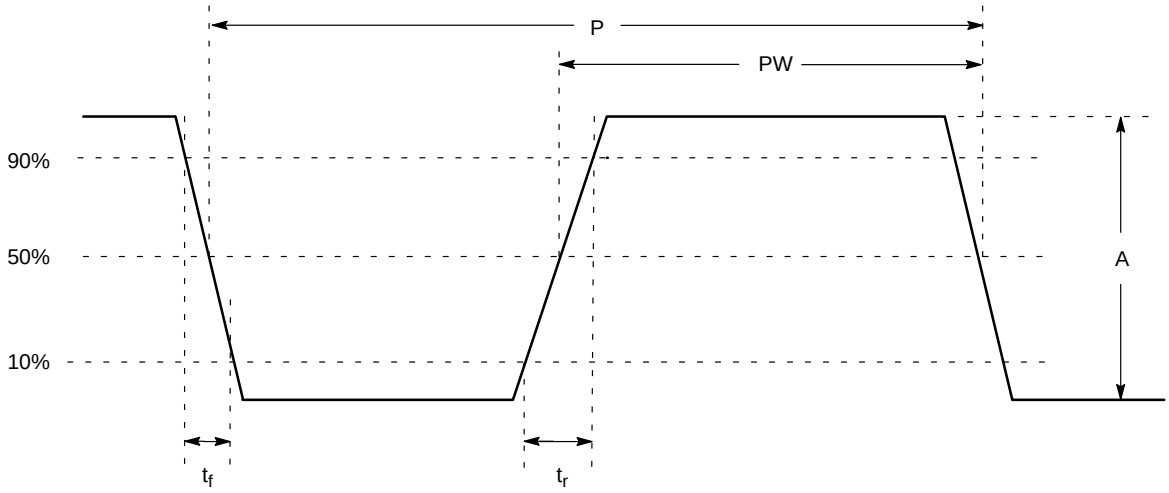

Figure 16. Bandwidth Determination Parameters

Where:

A = amplitude (V)
t_r = rise time (s)
t_f = fall time (s)
PW = pulse width (s)
P = period (s)
δ = duty cycle = PW / P
0 dB reference = 20 log $_{10}$ (2Aδ)
$f_1 = 1 / \pi P$
$f_2 = 1 / \pi t_r$ (Note: If $t_f < t_r$, then $f_2 = 1 / \pi t_f$)

A Bode plot of the trapezoid signal's frequency content is shown in Figure 17. At the frequency of pole f_1 the slope of the frequency response is –20 dB/decade, while at the frequency of pole f_2 the slope becomes –40 dB/decade. In general, the frequencies above f_2 can be ignored and the bandwidth of the signal is approximated by frequency f_2.

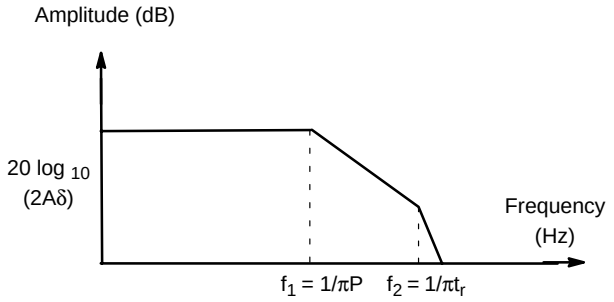

Figure 17. Bode Plot of Frequency Response

Step 2: Select the filter f_{-3dB} frequency

The filter's f_{-3dB} frequency is determined by the signal bandwidth of the signal, and whether the signal is analog or digital. The filter's f_{-3dB} frequency for analog signals is

typically set to the maximum frequency of the signal. In contrast, the filter's f_{-3dB} frequency for digital signals maybe either greater than or less than the maximum frequency. Often, it is desirable to limit the rise and fall times of digital signals because the radiated emissions that are emitted from the I/O cable are proportional to the signal bandwidth. Thus the filter for a digital data line sometimes has a f_{-3dB} frequency that is less than the signal's maximum frequency to reduce the signal's high frequency content by increasing the duration of the pulse transition times.

When the filter is used to limit the signal bandwidth, the pulse softness factor (S) can be used as a guideline to determine the amount of filtering that is appropriate. An S value of approximately 0.1 to 0.2, as shown in Figure 18, is recommended to limit the EMI consequences of the high frequency, but yet will allow for a signal that is a reasonable representation of the unfiltered signal. The signal bandwidth procedure show in step 1 can be used to select a pulse rise and fall time that results in the chosen S value.

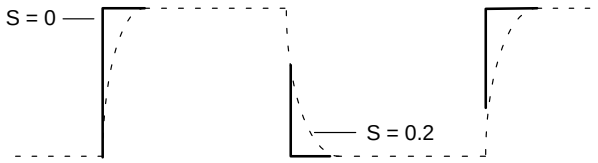

Figure 18. Softness factor S = t_r / PW

Step 3: Adjust the f_{-3dB} frequency for tolerance, temperature and voltage bias errors

After selecting the initial f_{-3dB} frequency, the designer should adjust the f_{-3dB} frequency to account for the tolerance and temperature errors of the resistors and capacitors. The variation of f_{-3dB} frequency due to the tolerances and temperature coefficient error of the Pi filter's resistor and capacitive terms can be estimated by calculating the Root–Sum–Square (RSS) of the error terms. The RSS method predicts a variance in the f_{-3dB} frequency point of 15.8% if the magnitude of each error term is equal to the values listed below.

$\varepsilon_{R_Tol.}$ = resistor tolerance error = ± 10%

$\varepsilon_{R_Temp.}$ = resistor temperature coefficient error = ± 5%

$\varepsilon_{C_Tol.}$ = capacitor tolerance error = ± 10%

$\varepsilon_{C_Temp.}$ = capacitor temperature coefficient error = ±5%

$$f_{-3dB} = \frac{1}{2\pi RC}$$

$$(\Delta f_{-3dB_Tol\&Temp})$$

$$\cong \sqrt{(\varepsilon_{R_Tol.})^2 + (\varepsilon_{R_Temp.})^2 + (\varepsilon_{C_Tol.})^2 + (\varepsilon_{C_Temp.})^2}$$

$$\cong \sqrt{(10)^2 + (5)^2 + (10)^2 + (5)^2}$$

$$\cong \pm 15.8\%$$

Zener based IPD EMI filters also have an additional error term because a zener's capacitance varies as a function of the bias or DC voltage. The maximum zener capacitance occurs at a 0V bias and the capacitance will be reduced by an amount that is proportional to the average voltage level of the signal. If the filter line is used as a digital transmission line and data is being continuously transmitted, the bias voltage will be equal to approximately the 50% point of the amplitude of the signal. Thus, the capacitance of the zener is effectively reduced and the capacitance (C) term in the filter equation should be adjusted. In contrast, if the data line is usually at 0VDC and is used only occasionally to transmit data, the zener bias level of 0V is representative of the signal, and it is not necessary to correct for the bias effect.

The correction factor for the zener bias voltage dependence of the capacitance can be determined from the filter's data sheet. For example, assume that the error term can be estimated as a 40% reduction in capacitance for a bias voltage that is equal to 50% of the diode's breakdown voltage. Also, assume that the magnitude of the tolerance and temperature errors is equal to 15.8%, as previously calculated. The equations listed below show that the initial f_{-3dB} frequency that is calculated from the signal bandwidth should be increased by 62% to account for the tolerance, temperature and bias voltage errors of the filter components.

$$f_{-3dB_corrected} \cong (\Delta f_{-3dB_Tol\&Temp})(\Delta f_{-3dB_V_bias})(f_{-3dB})$$

$$f_{-3dB_corrected} \cong (1.158)(1.40)(f_{-3dB}) \cong (1.62)(f_{-3dB})$$

Step 4: Determine the f_{-3dB} frequency shift of the filter with source and load impedances

The frequency response of the filter is dependent on the impedance of the driver and receiver circuits that are connected to the filter. The effect of the source and load impedance can be calculated from the filter transfer equations given in Table 2 of Application Note AND8026 (3) or can be determined by performing a SPICE circuit simulation.

Step 5: Specify the filter with 50 Ω source and load impedances

Specifying the filter with 50 Ω source and load impedances is often a source of confusion because the circuit impedances are not typically equal to 50 Ω. EMI filters are specified with a 50 Ω source and load impedance because that is the standard impedance of the test equipment used to obtain the frequency response data. The filter circuit's frequency characteristics can be measured using either a network impedance analyzer or a spectrum analyzer with a tracking generator as shown in Figure 19.

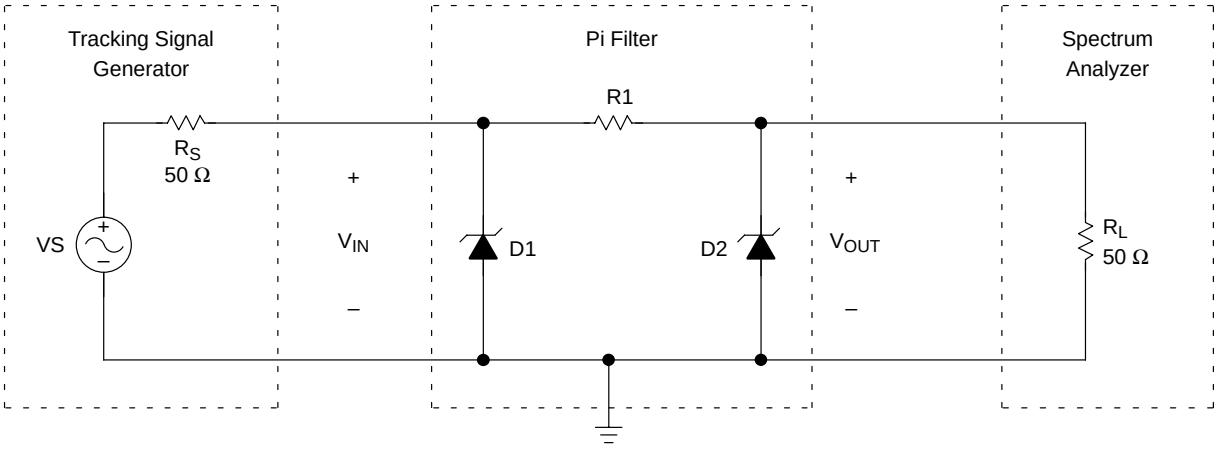

Figure 19. Zener Based RC Pi Filter Test Circuit with 50Ω Source and Load Impedances

The specifications that define a low pass filter are cut–off frequency (f_{-3dB}), insertion loss and the attenuation or rejection level of a specific high frequency. The cut–off frequency, or f_{-3dB} frequency, is defined as the corner frequency where the gain (attenuation) of the filter decreases (increases) by 3 dB from the low frequency gain (attenuation). The insertion loss is defined as the ratio of the power delivered to the load with and without the filter network in the circuit. The high frequency rejection specification is application specific and is used to verify the attenuation of a particular frequency. For example, it is critical in a cellular phone that the EMI filter attenuates the system's operating frequency; therefore, cellular phone filters will have a minimum attenuation level specified at 900 MHz.

Step 6: Select a filter configuration to meet the EMI and ESD requirements

The impedances of the circuits that interface to the filter network are an important factor in determining the effectiveness of the EMI filters. Series filter devices such as ferrite beads reduce the EMI current; thus they are effective in low impedance or high current circuits. In contrast, the Pi circuit is a shunt device that is most effective when used with high impedance circuits or low current circuits. For example, the Pi filter is an effective EMI filter on high impedance data line signals; however, the filter will not be a good choice for a low impedance circuit such as the data line signal's ground return line.

The decision on whether to use a Pi or a Tee filter is also based on the source and load impedances. In general, capacitors are most effective if they are connected to high impedances, while resistors/inductors are more effective when connected to low impedances. Thus, Pi filters are the best choice when both the source and load impedances are high, while Tee filters should be selected for low impedance circuits. The dividing point between whether an impedance is low or high is arbitrary, but 50 Ω is recommended as a guideline. Thus, classify an impedance that is less than 50 Ω as a low impedance and an impedance greater than 50 Ω as a high impedance.

In addition to its noise filtering function, the I/O filter device also provides ESD protection. All of the filter options will reduce the ESD voltage by virtue of their low pass filter configuration, but the filtered waveform may still be beyond the maximum input level of the transmitter and receiver circuits. The IPD Pi circuit configuration of two zeners clamps the ESD voltage to a safe level that is within a few millivolts of the zener breakdown voltage. The ESD design equations for the Pi filter are discussed in more detail in AND8026 (3).

Step 7: Verify the system operation with SPICE and/or prototype hardware

The last step in the EMI/ESD filter selection procedure is to verify the filter's operation with the transmitter and receiver circuits. The filter's effectiveness to provide EMI and ESD protection should be verified either by performing a detailed SPICE simulation or by testing prototype hardware.

First, the effectiveness of the filter in the circuit is very dependent on the grounding and location of the EMI filter on the PCB. In other words, the filter will not attenuate the noise signals unless the PCB is carefully designed. Application Note AND8026 (3) provides a list of PCB recommendations regarding the grounding and placement of the EMI filter, along with the artwork of the NZMM7V0T4 evaluation PCB.

Next, it is important to verify the filter's performance on the PCB with the receiver and transmitter circuits to ensure that there is no resonant frequency amplification at high frequencies. The ideal filter response is only practical in theory and all low pass filters will start to amplify frequencies that are greater than f_{-3dB} at some point due to parasitic impedances. It is usually very difficult to determine the parasitic parameters that are inherent in the PCB traces and IC connections that interconnect the devices; however, there are several commercial software packages available that can be used to evaluate the PCB's EMI characteristics (2).

Finally, the dividing line between not enough filtering or too much filtering to the point where the filtered signal is not representative of the original unfiltered signal is sometimes difficult to determine. This can be a problem when the filter is used to alter the rise and fall times of a digital signal. The filtered signals can be measured and the "S" factor can be used as a guideline to determine if the filtering level is appropriate.

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