

Design Considerations for ESD/EMI Filters: II Low Pass Filters for Audio Filter Applications

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APPLICATION NOTE

Background

For some time now portable electronic devices that have some sort of audio function have needed some type of Electro Static Discharge (ESD) protection. These ESD protection devices would be used to protect the audio input/output jacks and sometimes be located at the speakers or microphone in the portable device itself. These ESD protection devices provided nothing more than basic ESD protection from ESD that the device could expect from normal use.

In portable devices such as cell phones, there is the added concern with regard to the audio lines. Not only do they still need ESD protection, there are quite often requirements to filter out Electromagnetic Interference (EMI). The concern is that radiated or conducted EMI could be generated at the audio input or output and then transmitted to the higher frequency RF lines causing distortion. Or, RF transmission, radiated or conducted, could affect the audio lines.

If a discrete solution is used for both ESD protection and EMI filtering, the number of components could be three or more parts per audio line. That would consist of a single ESD component for ESD protection and an inductor/Resistor and capacitor combination to provide EMI filtering. For increased EMI filtering, more components are needed. Also, an EMI filter composed of discrete components quite often has some undesirable parasitics that may result in poor filtering. More importantly, a discrete solution requires a significant amount of board space. When board space is at a premium, the last thing needed is a large number of surface mount components.

One solution would be to integrate the ESD and EMI filtering functions on to a single piece of silicon. Doing this would not only reduce the number of components used for each audio line, but would reduce unwanted parasitics,

especially ground path inductance. For audio input applications at microphones, there are parts such as the *NUF2114* and *NUF2116*, each capable of providing ESD protection and EMI filtering for two audio lines using an RC "Pi" filter configuration. For audio output that may require an LC "Pi" filter, there is the *NUF2441* and *NUF2070*, that each can support two lines, and the *NUF4220* with four lines of protection.

Not all integrated ESD/EMI filters are the same. There are cases where using a series resistor in place of an inductor may be just fine, especially on the audio input side near the microphone where the network impedances are high. How many audio lines are there that need ESD protection and EMI filtering? What voltage of protection is needed for ESD protection? Would a unidirectional Transient Voltage Suppressor (TVS) diode be needed or would a bidirectional TVS diode be required? These are just a few of the considerations when choosing an ESD/EMI filter.

Types of Audio Applications

With regard to portable handheld electronic devices, there are two general areas where an ESD/EMI filter could be used. There is the input audio after the microphone, and then there is the audio output before the speaker. Each of these has its own requirements, particularly when considering the network impedance.

For today's cell phones, there are four areas where an audio ESD/EMI Filter may be placed. The most obvious place is next to the hands free connector. This is generally where an Electrostatic Discharge is most likely to occur. This is because the phone itself is incased in plastic and can hold some charge and the hands free set can hold another. If there is no ESD protection at this port, it is likely ESD will damage the more sensitive internal components.

Another concern at the hands free port is Radiated EMI. The wired lead of the head set can act as a long antenna. The concern is that if there are external sources of RF signals or background noise, these signals will be received by the hands free set and then be conducted to other signal processing components where it can be amplified and conducted to other portions of the phone. This can distort the signals that are meant to be received or transmitted by the cell phone causing a noticeable deterioration in sound quality.

Not as obvious as the hands free connector, is the speaker and microphone inside the cell phone itself. These too are susceptible to ESD and should be protected because they provide electrical paths to the more sensitive internal components. Though not nearly as much, there also should be some EMI filtering at both the speaker and microphone, for the same reason as the hands free connector. The distances of the microphone and speaker from (Digital to Analog Converter/Analog to Digital Converter (DAC/ADC), mean the traces are susceptible to picking up EMI that is generated by the phone itself. The concern is that the audio lines may allow cross communication between the phone's transmitter and receiver.

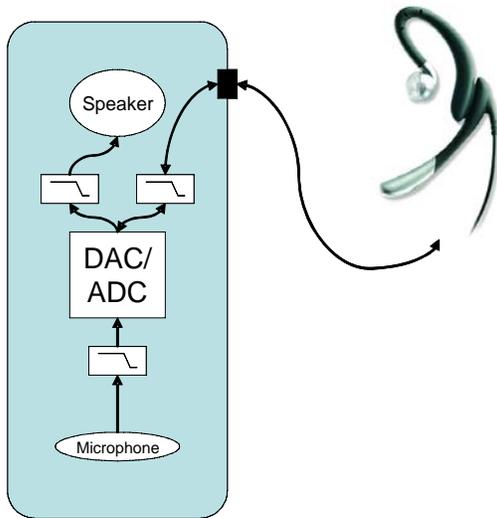


Figure 1. Simplified diagram showing where ESD/EMI filters should be placed in cell phones. The general locations for ESD/EMI filters are at the hands free port, with separate filters for the microphone and speaker, and individual ESD/EMI filters for internal microphone and speakers.

In a very simplified input/output configuration as in Figure 2, an ESD/EMI filter would be placed between the microphone and the ADC. The main differentiator between the microphone lines and the speaker lines is the network impedances. The impedances of the microphone lines tend to be much higher than the speaker lines. So much so that an RC type ESD/EMI Filter could be used. Because of the higher network impedance, the quality of the filter becomes dominated by the filter capacitance and the network impedance with the series resistance contributing little. How the network impedance affects filtering will be discussed later.

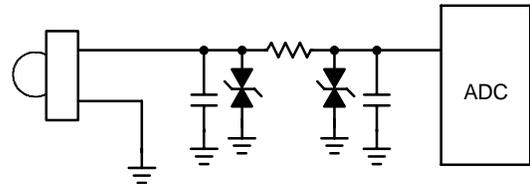


Figure 2. Simplified Example of the Placement of an ESD/EMI Filter for Audio Input

The other aspect of audio ESD/EMI filters is the audio output. Apposed to the audio input, the audio output has a lower network impedance. Because of this, an ESD/EMI Filter with low resistance and some series inductance would be preferred, such as a LC “Pi” configuration. How much inductance and capacitance may depend on what type of output stage is used. Because these filters are integrated, the size of the inductors are limited, and have more series resistance than an equivalent surface mount component.

Audio Output

We need to take a quick look at audio output stages. For the sake of argument, we can group the audio output stages into two groups. There are the more conventional “Linear” amplifiers, such as the Class A, AB, and Class B. And then there is the “non-Linear” Class D amplifier.

Even though the Class A, B, and AB are not truly linear, their output for the most part behaves linearly so long as the output is not driven to its voltage rails. In short, a small signal is amplified with few harmonics generated.

As a quick review, the class A and AB audio output stages have similar transfer characteristics. The primary difference between the two types is the Output power efficiency of the stages. They do not add much distortion to the amplified signal unless the signal is driven to one or both voltage rails.

So the concern is not the amplifier producing EMI, but rather EMI from some other source would use the amplifier as path into the portable device or phone.

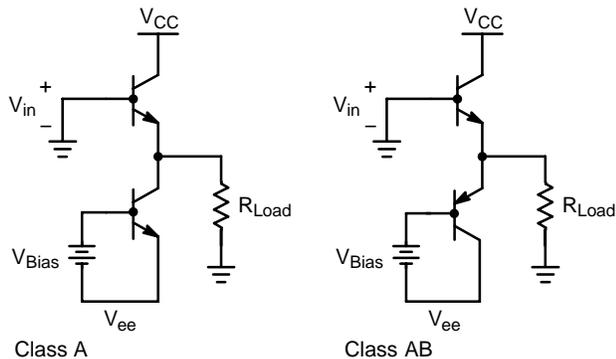


Figure 3. Basic configurations of a Class A and Class AB output stages. The class A is one of the more simple configurations, but is very inefficient. The Class AB has similar efficiencies to the Class B, but is compensated such that there is no crossover distortion.

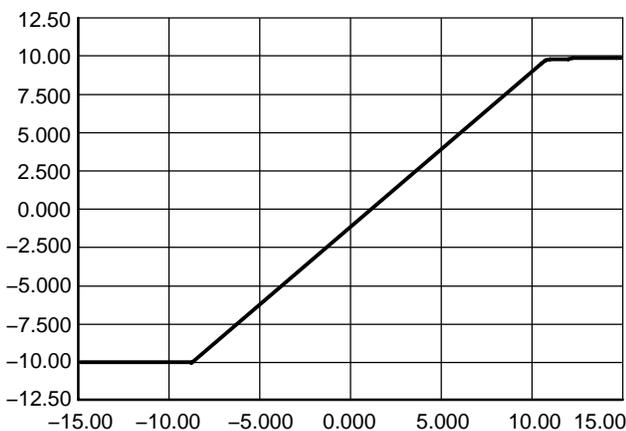


Figure 4. Basic Transfer Characteristic of either a Class A or Class AB Audio Output Stage

The Class B audio amplifier output stage, on the other hand, can distort an audio signal and generate low levels of EMI. The distortion would be generated at the crossover. This is the primary reason this configuration is rarely seen in use.

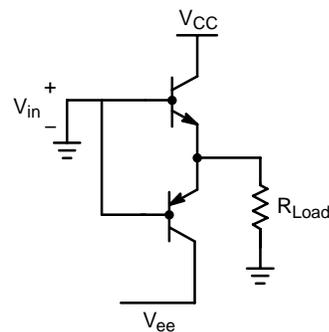


Figure 5. Basic configurations of a Class B. This configuration is not often used for audio applications because of the cross distortion.

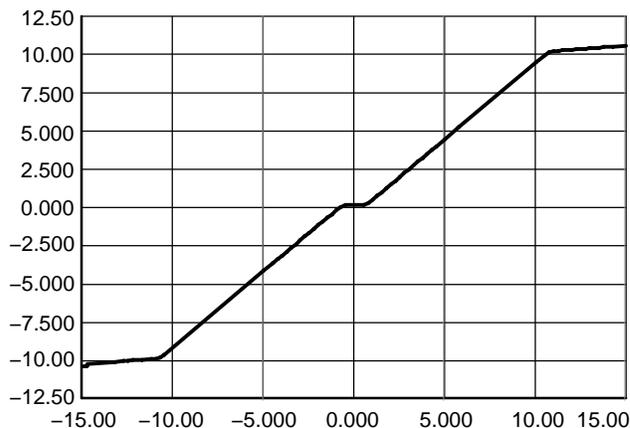


Figure 6. Basic Transfer Characteristic of a Class B Output Stage

The Class D amplifier, on the other hand, is very NOISY. A Class D amplifier is a “Switch Mode” audio amplifier. For many it has more in common with switch mode power supplies than a conventional amplifier. As “Switch Mode” implies, the audio signal is amplified through switching a Pulse Width Modulated (PWM) signal. Depending on the application, the switching speed may change. It is this switching that is of concern to EMI. Not only is the fundamental frequency of the switching cause for concern, but the rising and falling edges of the PWM signal contain high frequency components which can cause both radiated and conducted EMI. The higher order components can contain enough energy to interfere with a cell phone receiver. Of any time an EMI filter is needed, this is it.

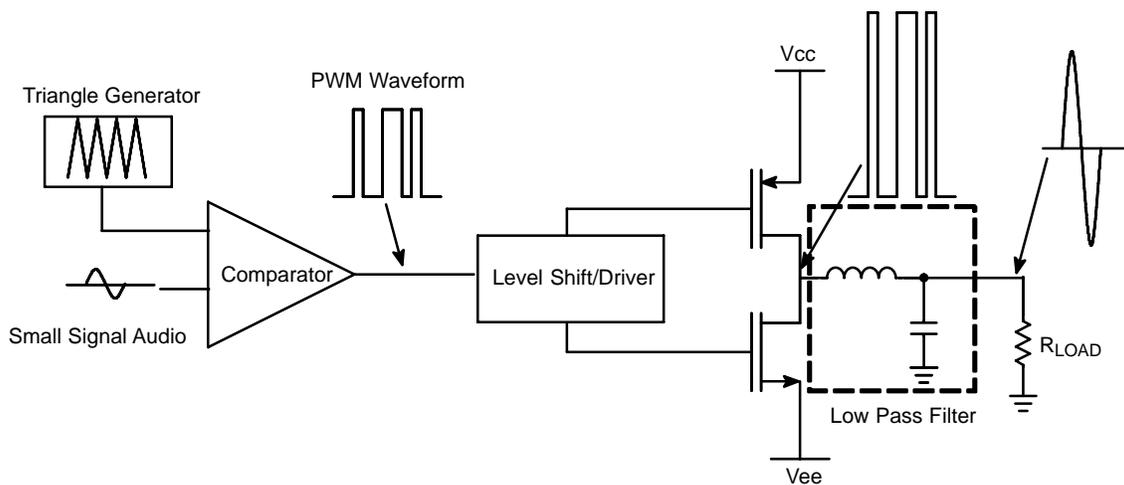


Figure 7. The Class D amplifier is not just a single stage, but a series. The basis concept is: An audio signal is feed into a comparator where it is compared to a continuous triangle wave. This converts the audio into a PWM signal whose frequency depends on the triangle wave. The PWM signal is put into some type of Level Shift/Driver. The Level Shift/Driver ensures that there is enough power and the right voltages to the drive output stage. The Output stage is typically a complementary inverting driver. Immediately following the output stage, is a low pass filter to filter out the higher frequency components of the amplified PWM signal leaving the amplified audio signal. This configuration is being employed more often to gain the benefit of very high efficiencies over all output power ranges at the cost of more components and complexity.

Types of Audio ESD/EMI Filters

Before getting into the filtering aspect of the ESD/EMI filter, we need to look at the ESD aspect of the component. Not all ESD protection is the same. ON Semiconductor application note AN8104, gives an excellent overview of ESD protection. An ESD protection component can have high ratings for ESD and still allow the components it is meant to protect to get damaged. This is because of two commonly overlooked aspects of ESD protection.

The first is the breakdown voltage of the component. It doesn't make sense to have a TVS that breaks down at 14 V, if the components it is meant to protect can be damaged at a lower voltage.

The second is how well the TVS clamps. For Transient Voltage Suppressor type diodes, this is the same as the Zener breakdown voltage. Ideally, during an ESD event, the voltage will be clamped at some determined voltage. Unfortunately, there is resistive contribution to the Zener diode when it breaks down. What this means is, when more energy or current is forced through the diode, the greater the magnitude of the voltage across the Zener diode or a higher clamping voltage. Because a TVS device may have a high ESD rating, does not necessarily mean it will protect a sensitive circuit, it means the TVS device will not be destroyed when exposed to a given level of ESD.

When it comes to ESD protection, there are two basic flavors of TVS diodes: Unidirectional and Bidirectional. The type of the diode determines the breakdown characteristics of the TVS diode.

Unidirectional

As its name implies, the Unidirectional TVS has a single reverse breakdown junction and a forward bias voltage, like any other diode. For this configuration, the Anode is connected to ground with the Cathode to the signal line as in Figure 8. As such, the audio signal's amplitude is not only limited by the supply voltage, but also limited by the breakdown voltage of the TVS. It also requires the audio signal to be offset.

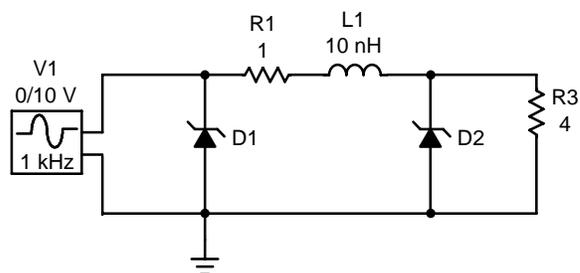


Figure 8. Basic Configuration of an ESD/EMI Filter using Unidirectional TVS Diodes

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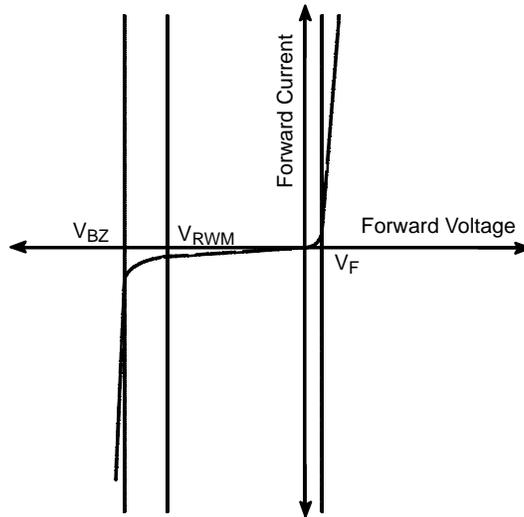


Figure 9. The IV characteristics of a TVS diode are typical for Zener diodes. The areas to note typically are the V_{BZ} and V_{RWM} .

When the audio signal is offset, such that it does not become negative, is when a Unidirectional TVS could be used. Also, the breakdown voltage (V_{BZ}) of the TVS should be great enough such that the Audio signal is less than the

Reverse Working Maximum Voltage (V_{RWM}). It is important that the V_{RWM} is large enough as to not distort the audio signal. But, V_{BZ} should not be so high as to render the TVS useless for providing ESD protection.

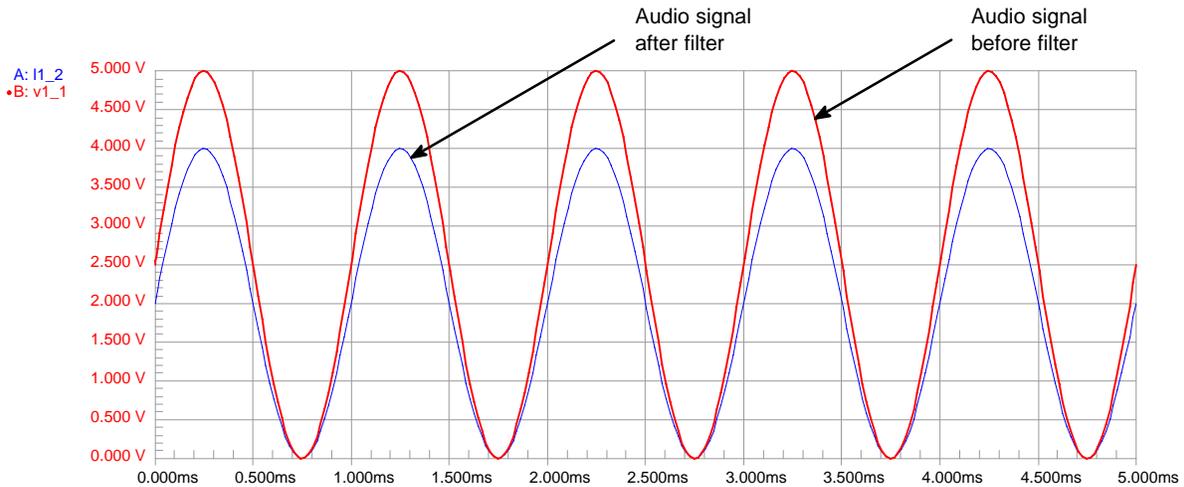


Figure 10. $V_{RWM} >$ Audio amplitude with DC offset. In this example the audio signal has an amplitude of 2.5 V with a DC offset of 2.5 V. The only attenuation to the signal should be caused by the series resistance of the filter. In this case the peak audio amplitude is taken to the V_{RWM} . Ideally, the audio signal operates above the V_F of the TVS and below the V_{RWM} .

If the V_{RWM} and V_{BZ} are not sufficiently large, the audio signal gets distorted or even clipped by the TVS as it breaks down. To ensure that the audio signal does not get distorted, it is best to pick an ESD/EMI filter with a V_{RWM} that is

slightly greater than the maximum producible audio signal. The V_{BZ} should not be so high that it does not provide protection.

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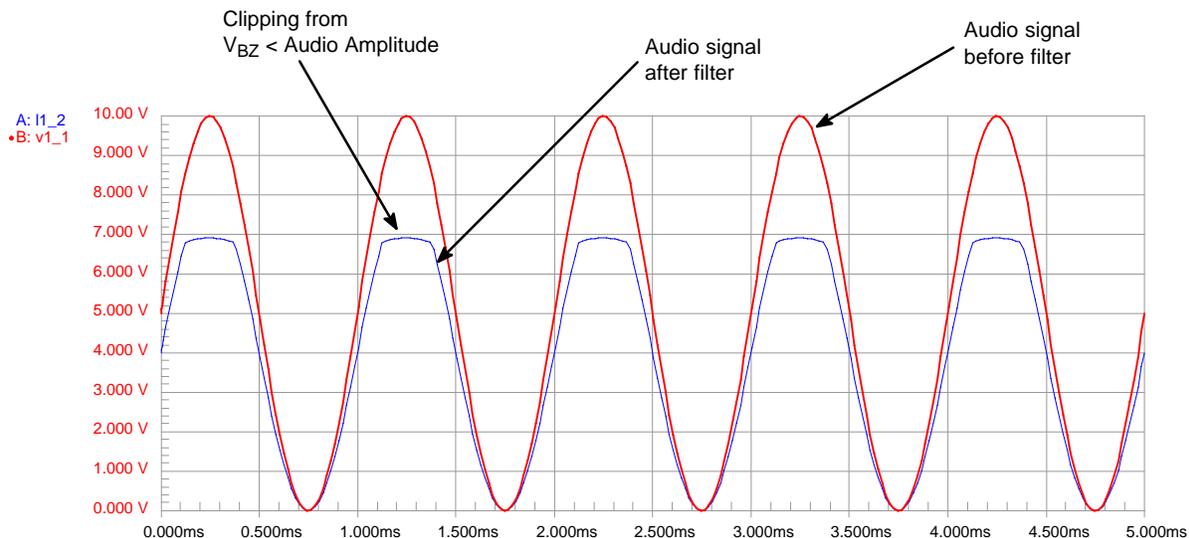


Figure 11. $V_{WRM} < \text{Audio amplitude}$ with DC offset. If the V_{WRM} is significantly less than the peak voltage of the audio signal, the signal will be clipped at V_{BZ} . In this example where the peak audio voltage is 10 V, while the V_{BZ} of the filter is less than 7.0 V. The breakdown voltage of the ESD/EMI Filter should be closer to 14 V.

If the audio signal is not offset and crosses 0 V and goes below the V_F of the TVS, the TVS will become forward bias and clip the negative side of the signal. If the signal does not

have a DC offset, then a Bidirectional TVS would be recommended.

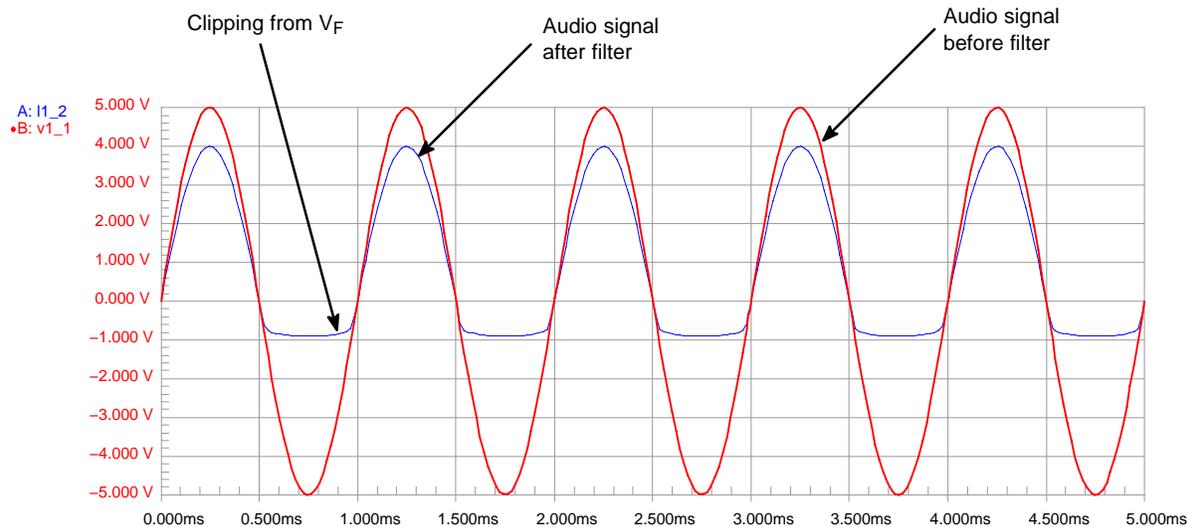


Figure 12. $V_z < \text{Audio amplitude}$ with no DC offset. If unidirectional TVS diodes are used on audio lines that are not DC offset, such that the audio signal may cause the TVS diodes to become forward bias and clip the audio signal below the V_F of the diode.

Bidirectional

The bidirectional TVS configuration is typically Anode – Cathode – Anode with the two TVS diodes sharing a common Cathode as in Figure 13. This configuration is used to minimize the internal resistance of the diode. Though a Cathode – Anode – Cathode configuration has similar electrical properties, when integrated into a single piece of silicon, there tends to be more resistance in the diodes.

This is the preferred configuration when the audio signal has little or no DC offset. The second TVS diode creates a lower voltage rail to prevent the type of clipping seen in Figure 12.

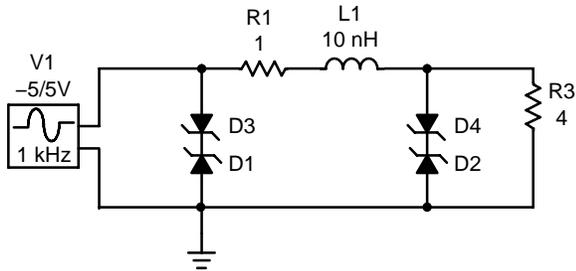


Figure 13. Basic Configuration of an ESD/EMI Filter using Bidirectional TVS Diodes

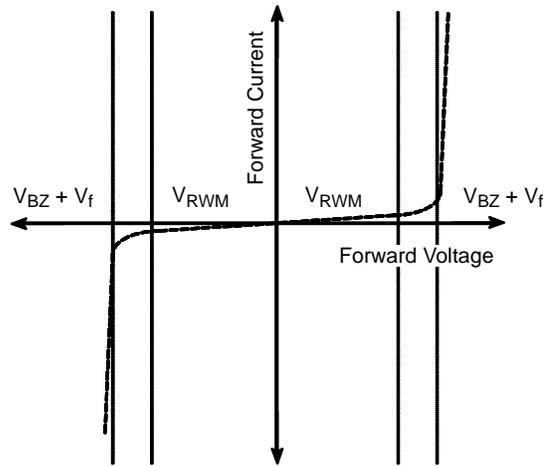


Figure 14. The IV characteristics of bidirectional TVS diodes are consistent with back to back Zener diodes. The actual breakdown voltage of a bidirectional TVS is actually determined by the breakdown voltage of one diode plus the forward active voltage of the other diode.

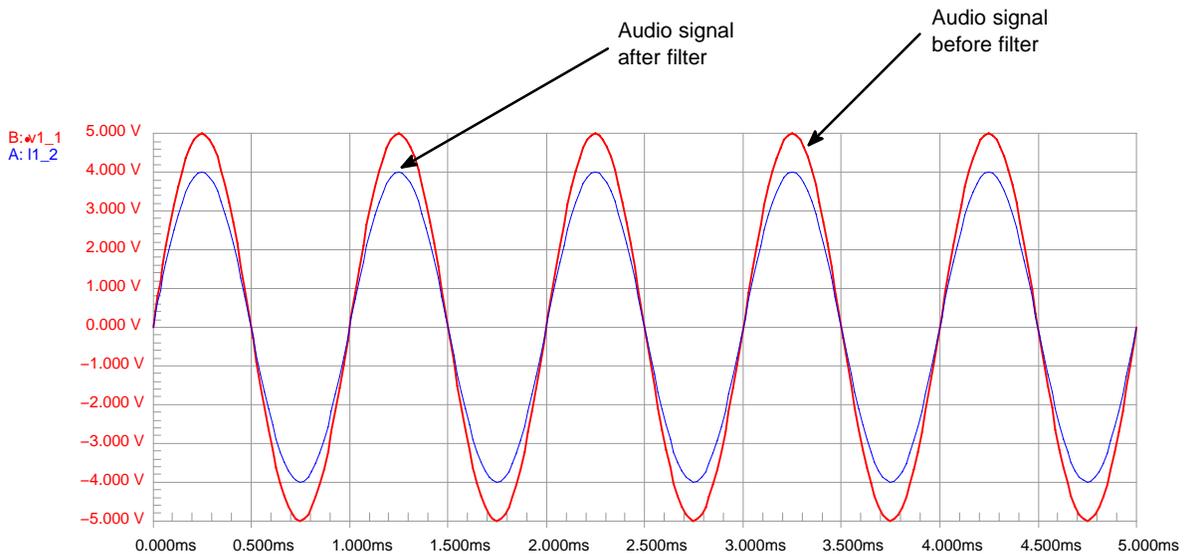


Figure 15. $V_z >$ Audio amplitude with no DC offset. In this example the audio signal has amplitude of 5.0 V with no DC offset. The only attenuation to the signal should be caused by the series resistance of the filter. In this case the peak audio amplitude is less than the V_{RWM} .

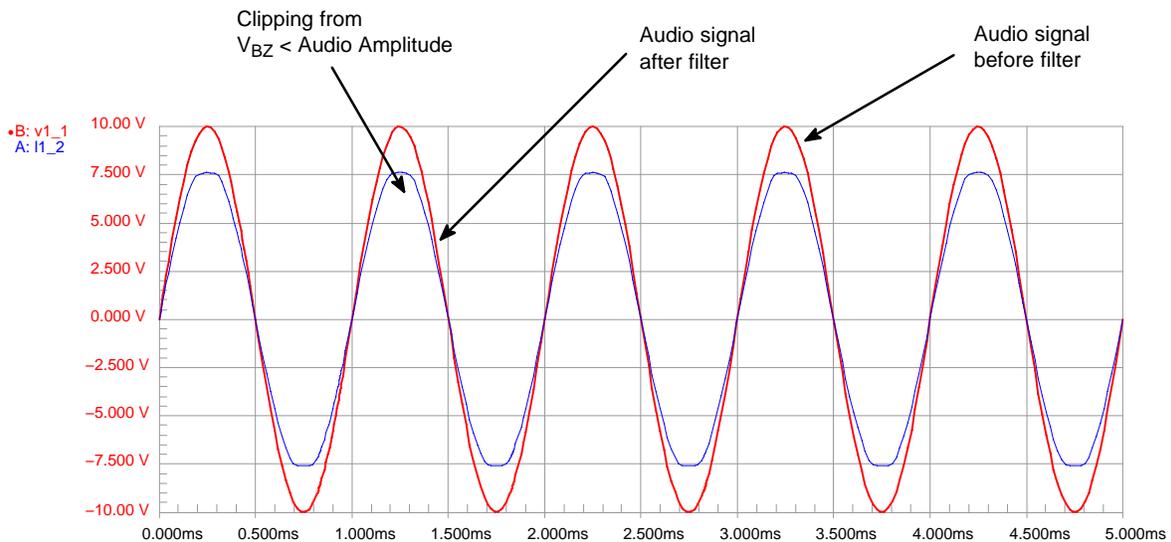


Figure 16. $V_z < \text{Audio amplitude}$ with no DC offset. If the V_{WRM} is significantly less than the peak voltage of the audio signal, the signal will be clipped at $V_{BZ} + V_F$. In this example the amplitude of the audio voltage is 10 V, while $V_{BZ} + V_F$ of the filter is about than 7.5 V. The breakdown voltage of the ESD/EMI Filter should be closer to 14 V for both directions.

Region to be Filtered

As with all EMI filters, the region to be filtered is the same for audio ESD/EMI filters. The basics of this region to be filtered are discussed in ON Semiconductor application note AN8200. There are a couple of other things to consider though. The first deals with why a Class D amplifier would need an EMI filter, when by design the amplifier already has a low pass filter. The second is how EMI filters behave on audio lines. The concern is that almost all data sheets for audio ESD/EMI Filters present their data under 50 Ω conditions. This would be fine if both the microphone and speaker lines had this impedance. As mentioned before, this is not the case. The audio input side has a high network impedance because of the microphone and the input side of the amplifier. The audio output side has a lower network impedance. The speakers tend to be current driven with an impedance between 4.0 and 32 Ω, while the output stage of the amplifier also has a low impedance.

Most Class D amplifiers use the basic low pass filter as shown in Figure 17. One of the problems that the low pass filters used to filter out the PWM signals, is that it often allows higher frequency components. The parasitics (Figure 18) in the surface mount components cause the low pass filter to behave more like a band rejection filter. That means a second filter is needed to filter out any signals that may interfere with cell phone RF frequencies.

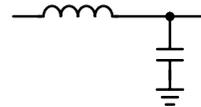


Figure 17. Ideal low pass filter consisting of a series inductor and capacitor to ground. This configuration should filter out all unwanted signals.

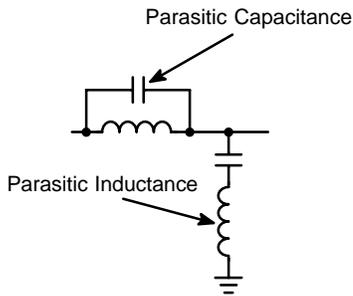


Figure 18. Class D low pass filter with inductive and capacitive parasitics. As will all surface mount components, there are associated parasitics. The surface mount inductor has an associated parallel inductance. The capacitor to ground has some inductance because of its physical length, but much of the inductance comes from the metal trace from the capacitor to ground. Much of the series parasitic inductance can be reduced if the capacitor can have the shortest possible path to ground.

When comparing the performance of an ideal low pass filter to an equivalent filter made up of surface mount components, as in Figure 19, it is clear the low pass filter does its intended job at the lower frequencies and falls short at the higher frequencies. Because of the resonances that are created within the individual components, the resulting insertion loss characteristics that allow unwanted higher frequencies to pass. To remove the high frequency signals requires a second filter in the case of a Class D system that specifically filters out the higher frequencies.

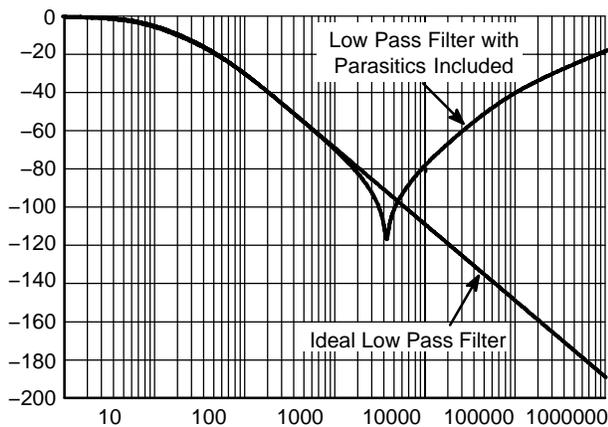


Figure 19. Ideal vs. Real at 50 Ω. Because of the parasitics in the surface mount components, the insertion loss characteristics of the filter make the filter behave like a band rejection filter and not a low pass filter. Frequency in kHz.

Regardless of whether the EMI filter is on the input side after a microphone or before a speaker, the integrated ESD/EMI Filter has the same basic topology. The filter

consists of either an “RC” or “LC” Pi type filter as in Figure 20. For microphone lines there most likely will be a series resistor with some value of capacitance on either side of that resistor. For speaker lines it is the same but using an integrated inductor. Where an integrated inductor lacks in Q factor when compared to surface mount inductors, makes up in space savings.

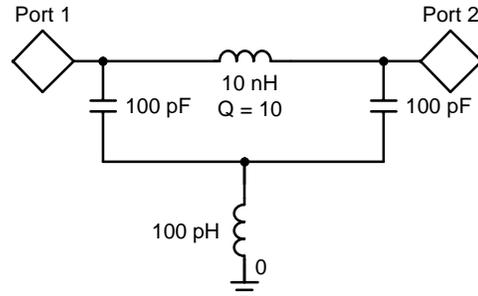


Figure 20. Basic Audio EMI Filter with Parasitic Ground Inductance

Even though the EMI filter is integrated, does not mean it is without its own parasitics. The package itself contributes some parasitic ground path inductance. On Semiconductor Application Note AN8200, explains this in greater detail. The affect of this ground path inductance can be seen in Figure 21 where the insertion loss begins to increase after 800 MHz.

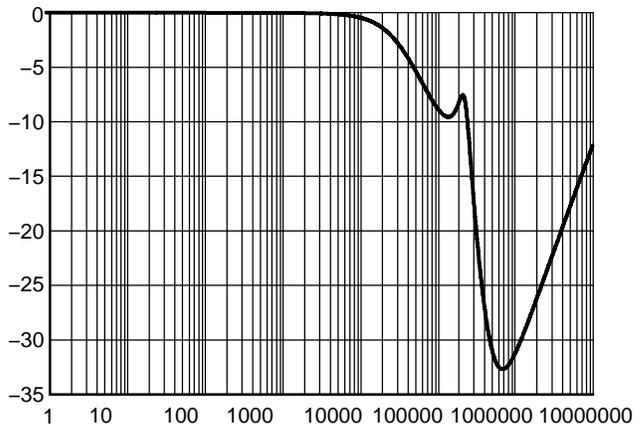


Figure 21. EMI filter at 50 Ω. The purpose of the EMI filter is to filter out signals in the range of 800 MHz to 2.5 GHz. Frequency in kHz.

Ideally, when the low pass filter of a Class D amplifier is complemented with an ESD/EMI Filter, both the switching noise from the amplifier and any other EMI are filtered out. Unfortunately, most Audio systems do not operate under 50 Ω conditions as shown in Figure 22. When the same filter network is looked at under a 4.0 Ω environment, the insertion loss response changes across the frequency spectrum.

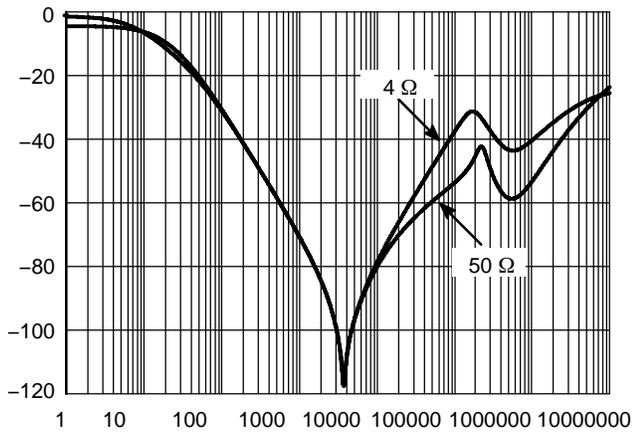


Figure 22. A comparison of both filters at 50 Ω and 4.0 Ω . When both the low pass filter for a Class D amplifier and an EMI filter are placed in series, both criteria are: The switching components of the amplifier are removed and EMI is also filtered out. The differences between the two conditions can be seen at both low frequencies and high frequencies. At low frequencies the filters behave like voltage dividers. As the network impedance becomes smaller, resistance in the filters attenuates the signal proportionately. At higher frequencies the EMI filter behavior is affected.
Frequency in kHz.

We can't forget the audio input side because their requirements are not the same as the audio output side. Because most data sheets present the insertion loss characteristics of the filter under 50 Ω conditions, the actual performance may be understated. Figure 23 shows how the same filter in a 50 Ω network behaves when in a 1000 Ω network.

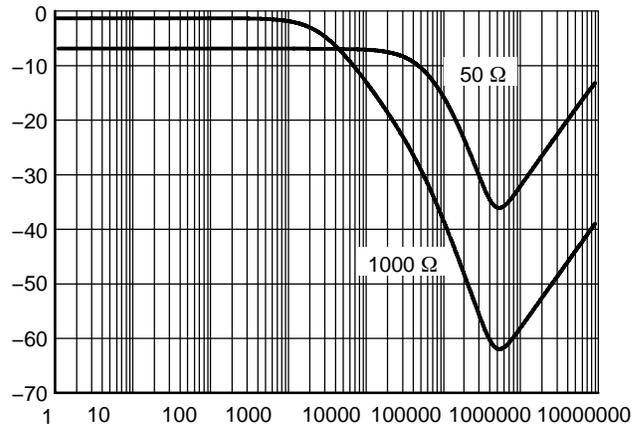


Figure 23. RC "Pi" filter with 100 Ω series resistance, 100 pF capacitance and 50 Ω network impedance. Frequency in kHz.

Choosing the Correct Filter and Other Considerations

When choosing ESD/EMI Filters, there are a few questions that need to be answered.

1. Is this filter for the audio input or output?
2. Is an LC filter required or will an RC do the job?
3. Can a Unidirectional TVS be used or is a Bidirectional TVS needed?
4. At what voltage should the TVS clamp at?
5. And what level of ESD protection is needed?

Once the first four questions are answered, the choice of an ESD/EMI Filter is narrowed. Because the TVS diode on audio ESD/EMI Filters are large, for EMI filters it is common that they already have the maximum IEC61000-4-2 ESD rating.

Once a filter is chosen, there are two final things to keep in mind. The first is place the ESD/EMI filter as close as possible to the source of ESD and EMI. For example, place the filter next to the hands free connector on a cell phone. The second is to keep the ground path as short as possible. Too much inductance in the ground path of the filter may cause poor filtering quality.

References

1. ON Semiconductor Application Note AN8200/D.
2. ON Semiconductor Application Note AN8104/D.
3. W. Marshall Leach, Jr., *Electroacoustics and Audio Amplifier Design, Second Edition*, Kenadall/Hunt, 2001.

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