RC and LC Lowpass Filters In Different Loading Environments

Filters must be selected based on the actual environments in which they will be used.

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INTRODUCTION

Lowpass filters respond differently in various loading environments. A designer may select a filter based on a curve published in a filter catalog or based on measured data from a network analyzer. Unless the actual environment is similar to the measured environment, the filter selected may not have the filter response that the designer desires.

LOADING ENVIRONMENTS

For digital applications, there are two common types of filters used: RC and LC filters (Figure 1). The configurations in Figure 1 are lowpass filters. These filters are used extensively for the purpose of EMI/RFI suppression on external data interfaces of digital computing devices. Depending on the application, RC lowpass filters may be more suitable than LC lowpass filters and vice versa. In general, LC filters are suitable for lines with shunt resistive terminations. RC filters are suitable for lines with no resistive terminations.

Figure 2 shows a generic voltage source, matching network, and load. One can easily translate this into digital applications (Figure 3). The voltage source in Figure 2 is the driver in Figure 3. The matching network is the transmission line. The load is the receiver. RL is the resistive termination that may be attached to the line, depending on the interface. Digital computing devices such as desktop PCs, notebook computers, and workstations have several standard external interfaces:

- Keyboard
- Mouse
- Parallel port
- Serial port
- Video (RGB [Red Green Blue] and LCD [Liquid Crystal Display])
- SCSI

These external interfaces can be separated into two groups: those with resistive terminations and those without resistive terminations. In the case of RGB video port and SCSI data lines, there is a shunt resistive termination RL at the end of the transmission line on the receiver side. LC filters are commonly used for both of these interfaces. Serial ports, parallel ports, keyboards, and mouse do not have resistive terminations. RC filters are commonly used for this group of interfaces.

Filter transfer function changes with load. The circuit in Figure 4 is an LC-type T filter. It can be connected to either a resistive load or a capacitive load. The transfer function is different for each load. H_{RL} is the transfer function of this T filter with a resistive load. H_{CL} is the transfer function of this T filter with a capacitive load. The trans-

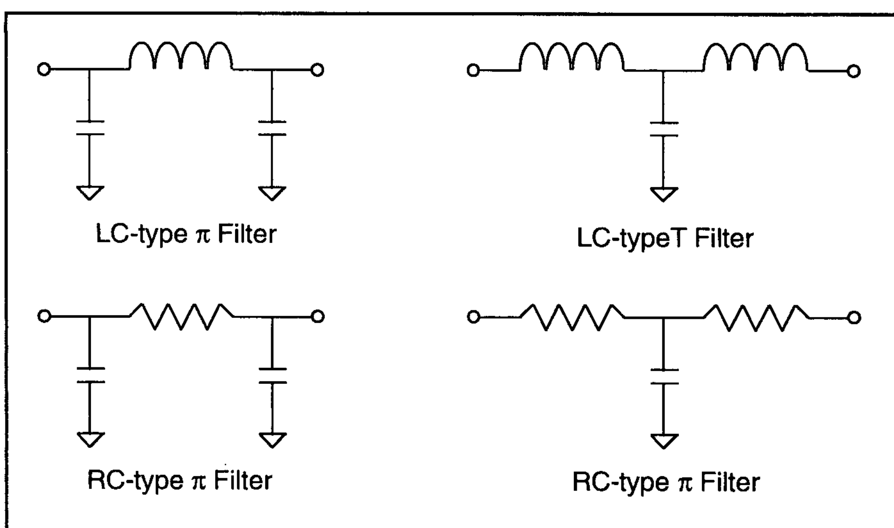

Figure 1. *Configurations for LC and RC Filters.*

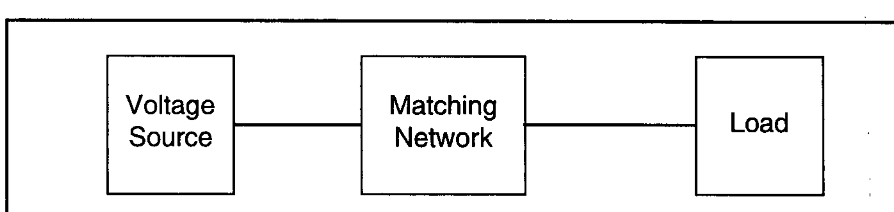

Figure 2. *Aspects of the Filter Environment.*

fer function of an LC-type T filter terminated with a resistive load can be expressed as:

$$H_{RL} = \frac{R_L}{s^3 L_1 L_2 C_1 + s^2 L_1 C_1 R_L + s\,(L_1 + L_2) + R_L}$$

The transfer function of a LC type-T filter terminated with a capacitive load can be expressed as:

$$H_{CL} = \frac{1}{s^4 L_2 L_1 C_1 C_L + s^2 (L_1 C_1 + L_2 C_L + L_1 C_L) + 1}$$

H_{RL} and H_{CL} are very different from each other. H_{RL} has 3 poles and H_{CL} has 4 poles. This means the transfer function of a LC-type T filter in a SCSI environment will be different from the transfer function of the same filter in a parallel port environment.

Figure 5 is an LC-type T filter with 240 nH of inductance and 33 pF capacitance. It is connected from a sweep source of 50 ohms generator impedance. On the other side of the filter is the load. The load can be a resistive load or a capacitive load.

Figure 6 shows filter behavior when the filter is connected with a 50-ohm load. The filter has a nice roll off with a corner frequency at about 88 MHz. The same filter is now connected to a capacitive load. The load capacitance is 5 pF.

Figure 7 shows the transfer function of the same filter with the 5-pF capacitive load. By changing the load from a 50-ohm resistor to a 5-pF capacitor, the corner frequency shifted from 88 to 169 MHz. The smooth in-band insertion loss disappeared. The pass band ripple became very large. Two resonances became apparent: 48 MHz and 158 MHz. Figure 8 is a composite plot of frequency responses showing changes in filter behavior with a 50-ohm load and 5- and 12-pF loads.

SAMPLE SCENARIO

A design engineer selected a filter based on a 50-ohm measurement shown in the catalog. The engineer used this type of filter to filter video data lines going to the LCD panel. As a result, the performance was not what was expected. The corner frequency shift (from resistive load to capacitive load) caused unwanted frequency to pass within the system. The resonances in band caused stability problems for the system. The instability in the system created more noise. The original purpose of the filter was to reduce noise in the system. Placing a filter in an environment based on data of the same filter in a different environment actually degraded performance.

Figure 9 is an RC-type T filter. H_{RL} is the transfer function for a resistive load. H_{CL} is the transfer function for a capacitive load.

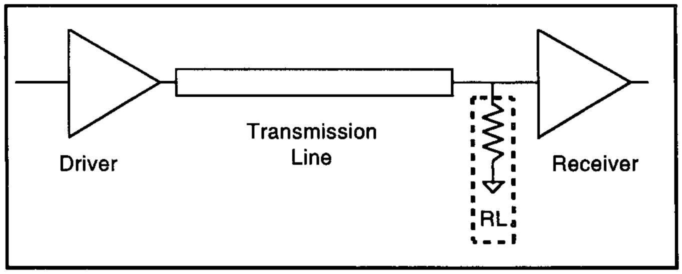

Figure 3. *The Digital Environment.*

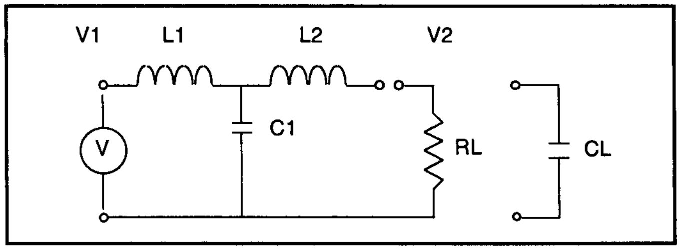

Figure 4. *Generic LC-Type T Filter.*

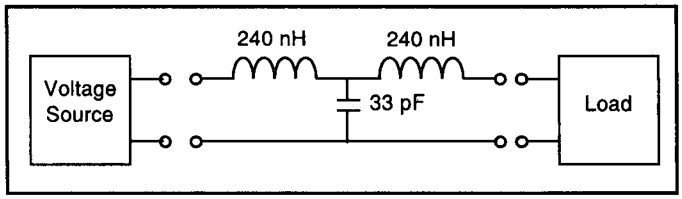

Figure 5. *LC -Type T Filter with 240 nH of Inductance and 33 pF of Capacitance.*

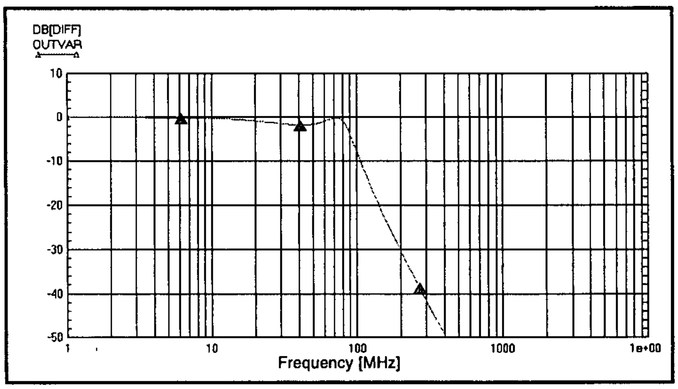

Figure 6. *Filter Behavior when Connected to a 50-ohm Load.*

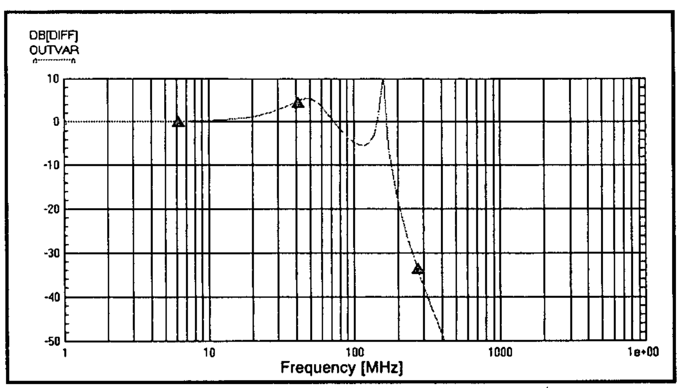

Figure 7. *Transfer Function of a Filter with a 5-pF Capacitive Load.*

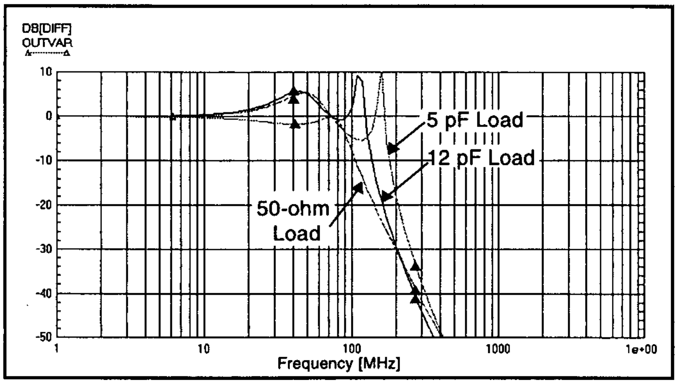

Figure 8. *Changes in Filter Behavior.*

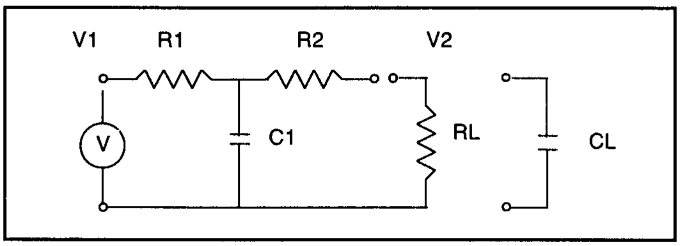

Figure 9. *Generic RC-Type T Filter.*

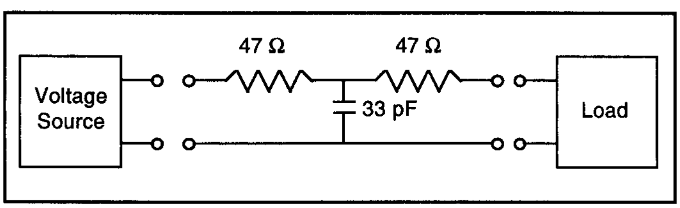

Figure 10. *Specific RC-Type T Filter.*

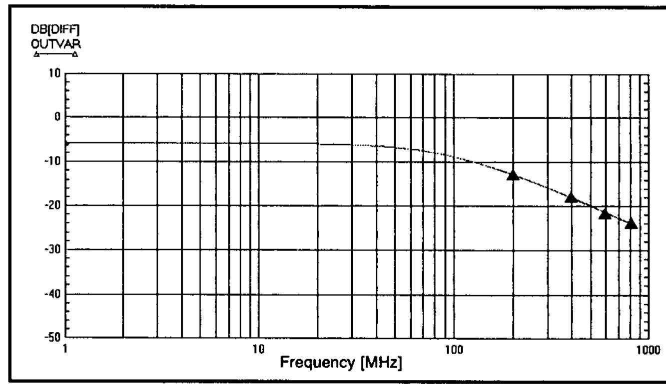

Figure 11. *Frequency Response in a 50-ohm Environment.*

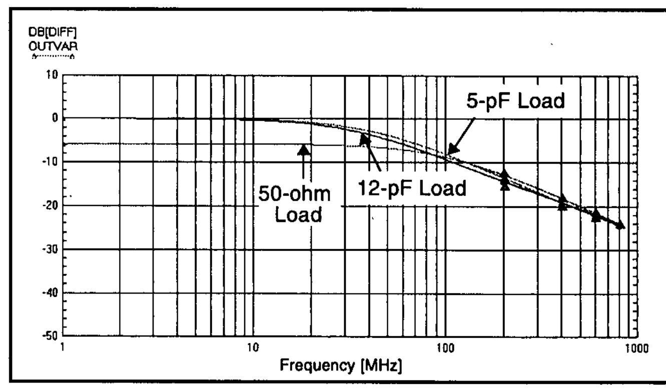

Figure 12. *Frequency Response with 5-pF and 12-pF Loads.*

$$H_{RL} = \frac{R_L}{s\,(R_L R_A C_1 + R_B R_A C_1) + R_A + R_B + R_L}$$

$$H_{CL} = \frac{1}{s^2 (R_A R_B C_1 C_L) + S\,(R_B C_L + R_A C_L + R_A C_1) + 1}$$

H_{RL} shows that load resistance plays a significant factor in the in-band attenuation. If $R_L = 50$, R_A and $R_B = 47$, the transfer function at 0 Hz will be approximately 1/3. This means significant in-band loss. On the other hand, H_{CL} showed no in-band loss at 0 Hz. If a designer rejected an RC-typeT filter based on too much in-band loss, as shown in a 50-ohm data plot, the designer may have rejected the filter for the wrong reason.

Figure 10 is an RC-type T filter. The value for R is 47 ohms, and the value for the capacitor is 33 pF. Figure 11 is the frequency response in the 50-ohm environment. The in-band insertion loss is about 5.8 dB. The corner frequency of this filter is 102 MHz (5.8 dB + 3 dB.)

Figure 12 shows frequency response of the same filter with 5 pF and 12 pF loads. The loads changed the corner frequency of this filter. The original in-band insertion loss of 5.8 dB at dc disappeared by changing from a 50-ohm resistive load to 5- and 12-pF capacitive loads. The corner frequency shifts in with an increase in capacitance. The corner frequency of the filter with 5 pF is 43 MHz, and the corner frequency of the filter with 12 pF is 36 MHz. There is no resonance within the passband that can create a stability problem.

From the transfer functions and from simulations, the LC-type T filter in an environment with resistive termination showed little in-band insertion loss, and it attenuated out-of-band signal rapidly with the help of three poles. LC-type T filters did not behave quite as well in an environment without resistive termination. The additional pole from the capacitive load with certain combinations of inductors and capacitors can cause instability. RC-type T filters have serious problems in environments with resistive terminations. The transfer function indicates that the RC-type T filter has only one pole with serious in-band attenuation. The RC-type T filter in environments without resistive terminations (capacitive loads) actually fared better. The transfer function has two poles. The attenuation at low frequency is minimal. Based on these assessments, the LC-type T filter is good for an environment with resistive termination. The RC-type T filter is good for an environment without resistive termination.

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CONCLUSION

The key to filter selection is to compare apples with apples. If the filter exhibits good response in the 50-ohm environment, the filter will perform in a 50-ohm environment, but the filter response will definitely be changed in a different environment. There are several ways to check if the filter is suitable. One way is to check values via transfer function. Another way is to simulate filter response in a given environment. It is important to understand the environment and filter requirements in order to make an effective filter selection.

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