TECHNICAL PAPER

AVX EMI Solutions

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Abstract

EMC compatibility is becoming a key design parameter for a most designers of electronic systems. This paper compares the efficiency and effectiveness of various EMI filter options available to designers. Integrated Thick Film LC T filters are shown to be a cost effective method to improve board level EMC performance while shrinking system design size and keeping costs minimized. A general recap of EMI sources is given as well as a brief recap of PCB layout and optimization rules.

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Introduction

By definition **EMC** is ability of electronic equipment to operate as designed in its intended electromagnetic environment without either causing interference to other equipment or suffering interference from other equipment. As systems shrink in size, become more portable, and more networked/interconnected, EMC is of huge concern to overall system performance. A system that has poor EMC capability can easily become ‘locked up’ or even worse can experience flipped bits thereby generating an erroneous output.

Generally speaking EMC standards fall into two classifications:

1. Immunity Standards – these standards define methods and conditions by which equipment is tested for immunity to unwanted signals. There are many different types of immunity requirements that a particular PC board or system can be required to meet. Generally, we can group the requirements to be:
   - Immunity to transient voltages
   - Immunity to RF fields of differing magnitude and frequency.

2. Emission Standards - these standards define the maximum amount of interference or noise that the equipment under test can generate.

The definition of **EMI** is any electrical disturbance that interferes with normal operation of electronic equipment. Sources of EMI include cell phones, computers, transmitters, system clocks, data lines, oscillators, receiver local oscillators, voltage regulators, power lines, etc. Broadly speaking, all PCB based high-speed digital signals can be a source of EMI.

Designers that minimize EMI sources within their designs typically create systems that have relatively good EMC performance. However, even in this case care must be taken to harden susceptible portions of the design as EMC standards require passing both emissions and susceptibility performance requirements.

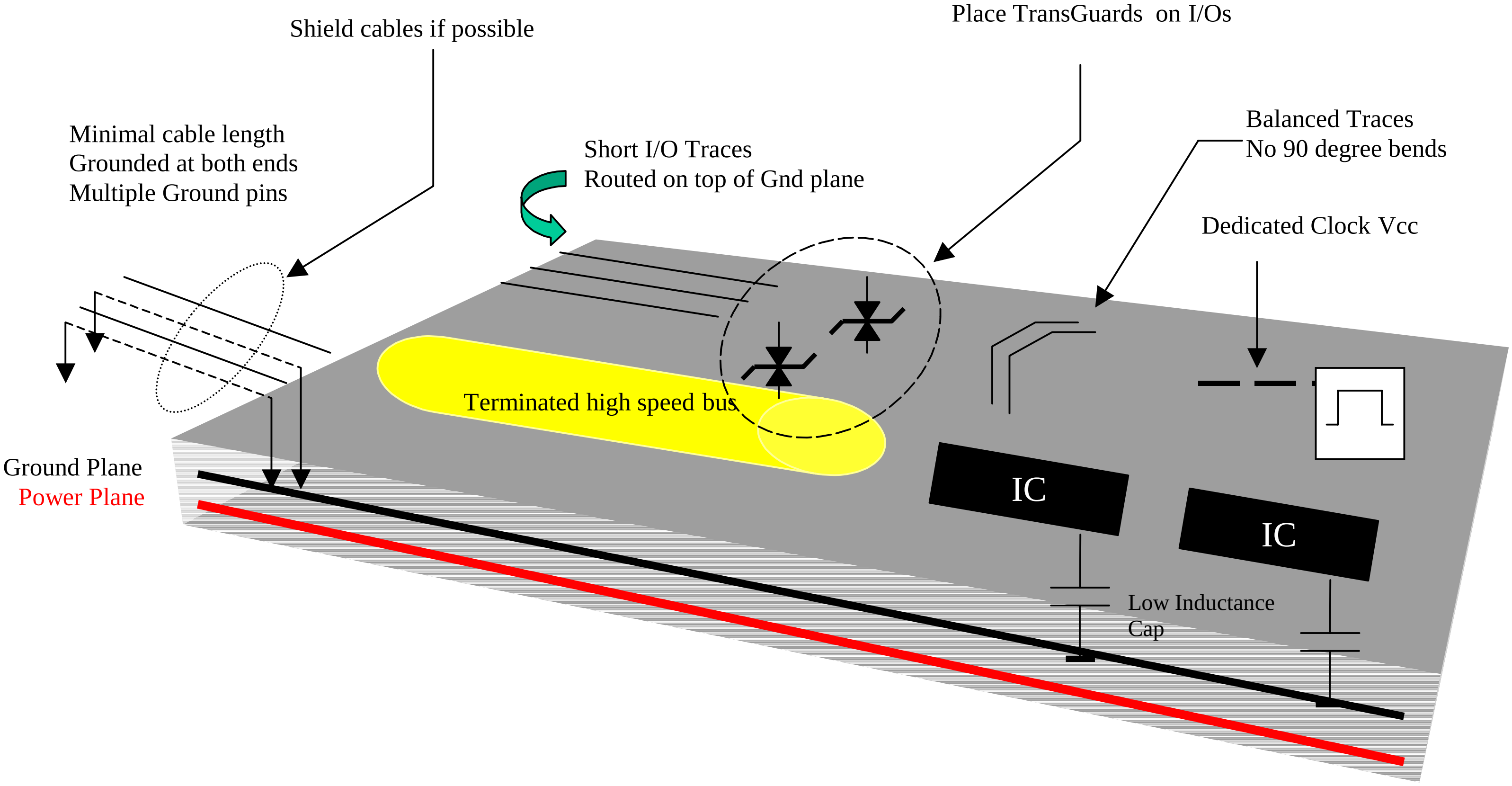
Meeting International EMC Specification Requirements

One of the first steps towards optimizing a system's EMC performance and reducing EMI is through conservative board layout early in the design process. However, in nearly all cases board optimization cannot eliminate EMI problems. Typically, transient suppression ***and*** EMI filtering methods must be additionally employed. The rigorous design effort is not lost as board level transient suppressors and EMI filters (added in the second phase of EMC hardening) are typically more efficient when used on a board that has gone through some amount of board layout optimization.

Following these rules typically reduces the magnitude of EMI encountered on a particular design. An illustration of how these board layout rules could be implemented is shown in Figure 1.

Briefly the top 10 board layout rules are:

1. Use a MultiLayer PCB with large Vcc and Ground planes.
    - If this is not possible create a ground grid.
    - If this is not feasible connect all grounds to a common point.
2. Use proven Decoupling methods
    - Use a high frequency decoupling capacitor at each IC
    - Use a high frequency decoupling capacitor at the regulator
    - Connect decoupling capacitors in the lowest inductance method possible
    - Route power and ground close to one another
3. Keep I/O traces short
    - Route I/O traces close to the ground plane
    - Place connectors on top of the ground plane
4. Use minimal cable length for connections
5. Terminate high speed lines
6. Shield cables if possible
    - Ground both ends of cables
    - Consider multiple grounds on a ribbon cable
7. Protect ESD sensitive components with a Transient Voltage Suppressor
    - MLVs clamp bi directionally in the on state and like EMI filters in the off state
    - Place the MLV as close to the transient source as possible
8. Consider a dedicated Vcc line to clocks
9. Consider limiting the number of 90° trace features. Two 45° trace features typically radiate less.
10. Use balanced trace design if possible



Board Layout Rule Examples
Figure 1

As previously stated, in a real world practical sense, these board layout optimization schemes will not reduce all EMI and improve EMC performance. Designers will experience a need to troubleshoot the board for sources of EMI as well as susceptibility to EMI. Then appropriate steps must be taken to eliminate weak areas of the design. We will first discuss concepts of EMI source identification and then discuss methods of hardening designs.

Conditions needed for EMI

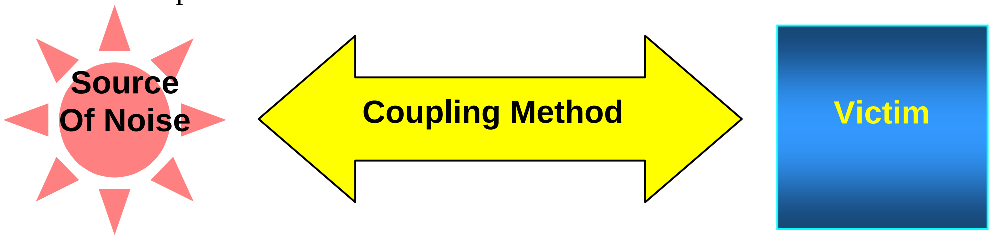
EMI sources can be external or internal to a system or board. An example of an external EMI source is RF power from a cell phone (which can radiate both back into the phone or into other systems). Another example of an external EMI source is lightning.

The most common types of internal EMI sources are clocks, high speed data lines, and large di/dt variations due to high-speed digital logic.

No matter what the source of EMI – internal or external, three elements must be present for EMI problems to occur:

- A source of noise

- A coupling method
- A susceptible victim available



All three elements must be identified to effectively fix any given EMI problem. Optimization of these 3 ‘problem areas’ must occur for an *IDEAL* EMC solution. That is:

- Noise sources must be eliminated, controlled or attenuated.
- Coupling methods must be broken or minimized
- Victim circuits and elements must be hardened

In the real world, designs can sometimes pass EMI requirements by sometimes optimizing as little as one of the 3 preceding fixes.

Often, the susceptible victim is typically the easiest portion of the puzzle to identify. For example, LCD screens lose picture content if not properly filtered in an RF environment. A CMOS camera may lose resolution or signal all together in an RF or transient environment. All these are easily identified. Susceptible victims will typically be hardened through the addition of increased filtering at their input/output function as well as better power supply isolation and filtering. Transient suppression as well as EMI filtering methods will be discussed later in this paper.

Coupling Methods are not as easy to identify. There are three coupling methods that can transport energy from the source to the victim:

- Energy can be radiated
- Energy can be conducted
- Energy can be induced

Typically, most EMI problems are either conduction, or a combination of conduction & radiated means. Many times filtering is the best option for designers to eliminate emissions and susceptibility problems of a design.

Common EMI Fixes

EMI attenuation and EMC compliance is such an application specific concept that we will concentrate on a single, high volume problem: *LCD EMI attenuation and EMC hardening for cell phones.*

The most common sources of radiated EMI to which any phone is subjected is the output frequency of the phone. That is, in any cell phone the transmitted RF energy is intentionally radiated to a cell phone base station to place and maintain a call. That RF is also unintentionally radiated to every I/O port, accessory port, LCD screen, slotted opening and non-shielded plane on the phone. Clearly any EMC hardening of the phone must include an optimized attenuation (through filtering) of the primary frequency in use on that cell phone. In our example, we will approximate these frequencies as 900 MHz and 1800 MHz. Certainly other transmit frequencies exist – this is just one example of many different possibilities.

Other components of EMI generated from within a cell phone are system clocks, digital to RF block interfaces, DSP and glue logic data streams and LCD drivers. It is important to note that EMI from the LCD driver circuit is enhanced by radiating off a flex connector that runs to the LCD. (Further, that flex connector also acts as a fairly efficient antenna to capture RF energy from the 900 and 1800 mhz RF output from the cell phone under discussion.

Why LCD Drivers radiate

In an ideal design, the respective loads into which each of the signal sources are connected would consume all of the signal energy switched during the driving of an LCD. Therefore, no energy would be available for radiation as noise.

This is design would be achieved by terminating each signal source into a load equal to it's source impedance; the condition required for maximum transfer of power. The connecting interfaces must exhibit zero loss, and have transmission line impedance equal to their respective source and load impedances. When these conditions are met, the load would absorb 100 percent of the power from all signal sources, and no signal energy (noise) would be radiated.

This design scenario is unable to be achieved in the LCD driver circuit. Further, the level of power radiated from the RF output at the antenna and conducted into the flex connector as EMI must be attenuated. Therefore a filter must be implemented to reduce reflected noise generated EMI as well as attenuate EMI from the cell phones RF output.

Understanding the flex connector data stream environment

Digital circuits are best described in the time domain. We commonly hear specifications of switching times of a chip, rise times and time delays. This is a valid parameter since at any particular point in time their logic state is either a 1 or 0.
Noise is best described in the frequency domain. Noise radiates and designers need to know the specific frequency that is causing EMI problems. Once that frequency is known filtering methods or shielding methods can attenuate it.

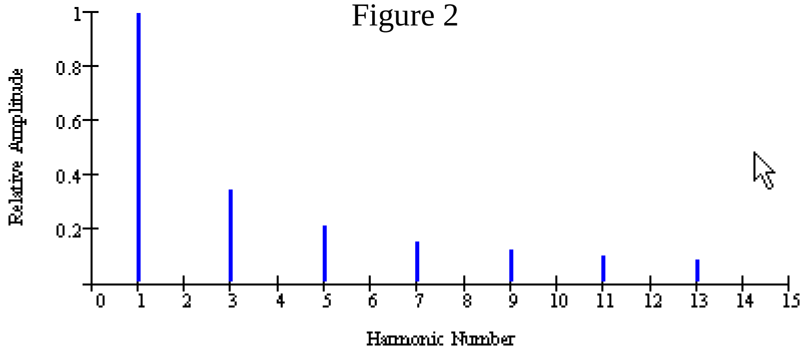
Fast Fourier Transform is a means for converting between the time (waveform), and frequency (spectrum) domain. One of the criteria for computing a Fast Fourier Transform (FFT) is that the analyzed waveform must be periodic, over the analysis period. The majority of digital signals and LCD driver circuits meet this characteristic. Additionally the circuits such as system clocks, digital to RF block interfaces and DSP glue logic meet this requirement.

When Fast Fourier Transform is applied to periodic digital waveforms, such as square waves or clock pulses, a family of harmonically related signals of diminishing amplitudes is identified. A pure square for example, consists of the sum of an infinite number of sine wave components whose frequencies are odd multiples of the fundamental (f_0, $3f_0$, $5f_0$, ...) and whose amplitudes decrease in proportion to the inverse of the harmonic number (1, 1/3, 1/5, 1/7,...). Real world square waves follow this trend, but because they have finite rise and fall times, even order components result that share the power distributed across the spectrum.

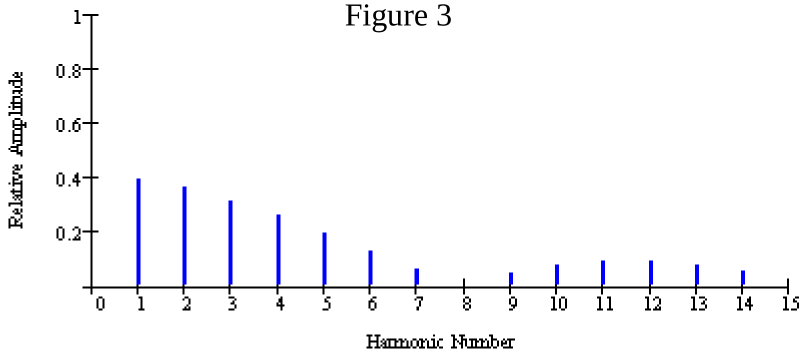
Generally, data flowing in the LCD flex connector will have a range of duty cycles. A comparison showing the spectrum of 3 equal amplitude digital signals each with duty cycles of 50%, 25%, and 12.5% forms a very crude but effective rule that will yield harmonic frequencies that are in need to be filtered (in addition to the 900 mhz and 1800 mhz previously identified in our cell phone example.

Duty cycles of 50%, 25% and 12.5% are represented in Figures 2 – 4.

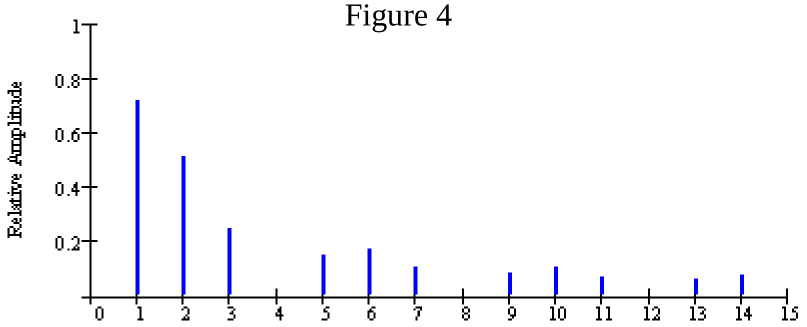
Spectrum of 50% duty Cycle
Figure 2



Spectrum of 12.5% duty Cycle
Figure 3



Spectrum of 25% duty Cycle
Figure 4



A number of things can be observed by inspection of Figures 2 – 4:

- The highest amplitude fundamental signal occurs when the duty cycle is 50 percent. This is reference from which all other signals are compared.
- The fundamental (position 1) frequency is always the highest amplitude component, regardless of duty cycle.
- Signal amplitude decreases toward zero for increasing frequency, reaching zero at 1/duty cycle.
- When duty cycle is 50%, no signals are present in even order harmonics
- The fundamental amplitude drops to 0.707 or 3dB (half the power), when the duty cycle is reduced to 25 percent.
- The spectrum consists of discreet frequencies spaced at regular intervals, not continuously spread across all frequencies.
- When summed together, the majority of the signal energy is contained in the first 3 spectral components.

Given the above analysis/observations we must target the largest magnitude noise components by frequency to achieve acceptable levels of EMC compliance. To do this we need to obtain a spectral plot or Fast Fourier Transform of the noise sources. The noise sources are typically LCD drivers, data stream, clocks, DSP and glue logic.

Filter efficiency comparison for optimum Cell phone EMC performance

A filter is a network of components that passes signals of certain frequencies and attenuates signals of different frequency. The basic types of filters we will discuss are:

- **Low Pass** - Low pass filters, only pass frequencies below the 3db cut off with little or no attenuation. Above the 3 db point signals are greatly attenuated
- **High Pass –** High Pass Filters pass frequencies above the 3db cut off frequency. Frequencies below the 3db point are highly attenuated.
- **Band Pass -** Band Pass filters pass a specific frequency spectrum while attenuating all others.
- **Band Stop -** Band Stop Filters (Band Reject filters) reject a specific frequency range and attenuate all others.

The graphical representations of each of these filters are shown in figure 5.

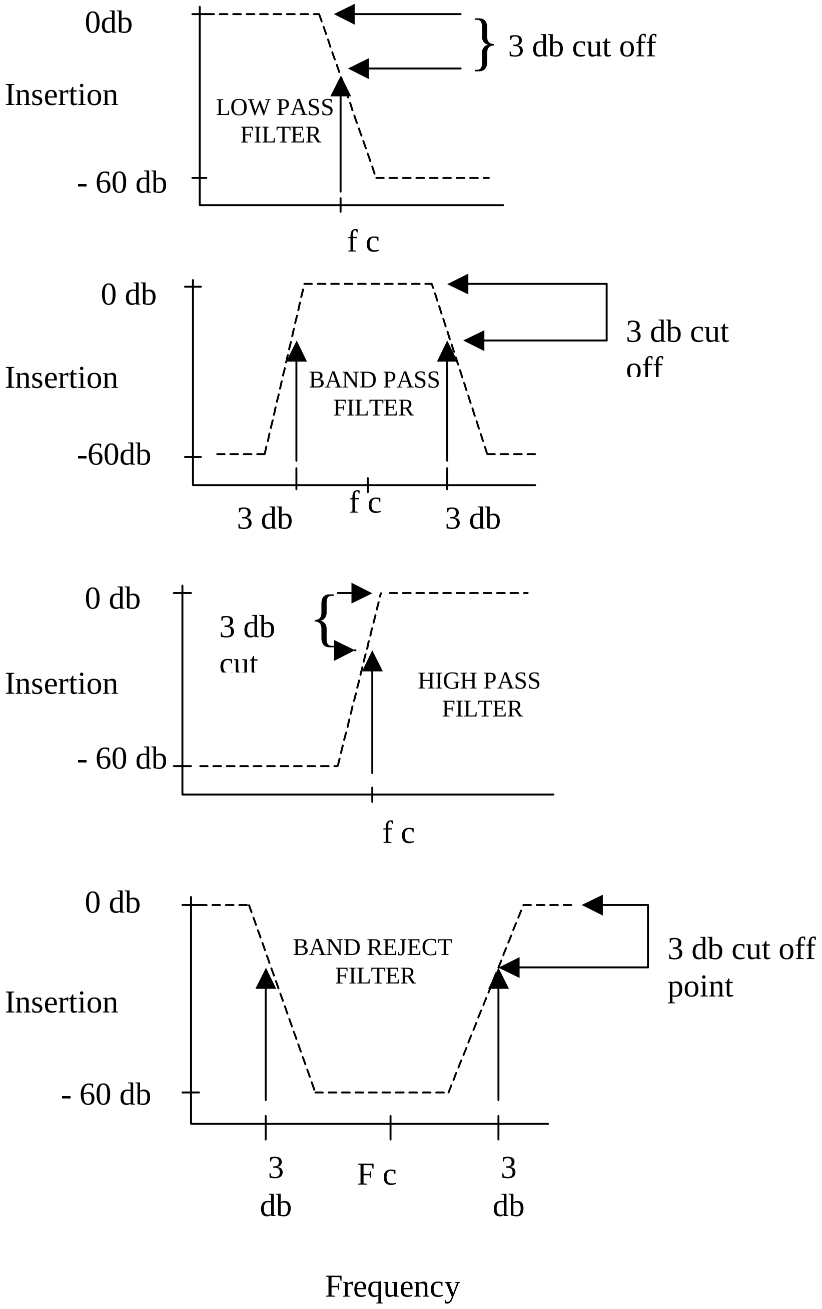


Figure 5 - Filter Types

Cell Phone Flex connector filtering – Low pass Filter or Band Reject Filter

The ideal filter for an LCD flex connector would provide a high attenuation to the portion of the RF output from the cell phone that gets radiated “into” of “from” the LCD screen. Those frequencies are 900 & 1800 MHz in this example. The filter would also provide adequate attenuation to EMI generated by the LCD driver circuits and associated glue logic within the phone. By taking care of each of these elements emissions and susceptibility will be hardened. Designers typically concentrate on two options for LCD flex connector EMI reduction – Low Pass filters and Band Stop filters.

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Discrete Low Pass Filter:

Typical discrete Low Pass Filters are either an RC or LC based filters. Examples of a second order LC and first order RC filter are shown in figure 6a and b.

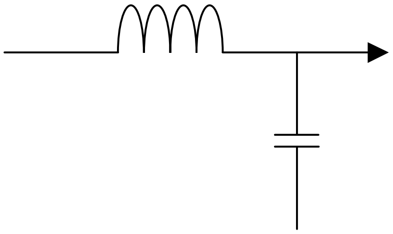


Figure 6a LC Low Pass Filter

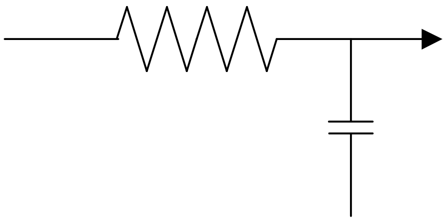


Figure 6b RC Low Pass Filter

Both exhibit limitations in effectiveness in some respects. Characteristics are:

- The slope of the filter is determined on the order of the filter. A second order filter falls off at 12 db/octave. A 3rd order filter falls off at 18db/octave. The roll off rate can be increased by 6 db/octave with each additional reactive element in the filter.

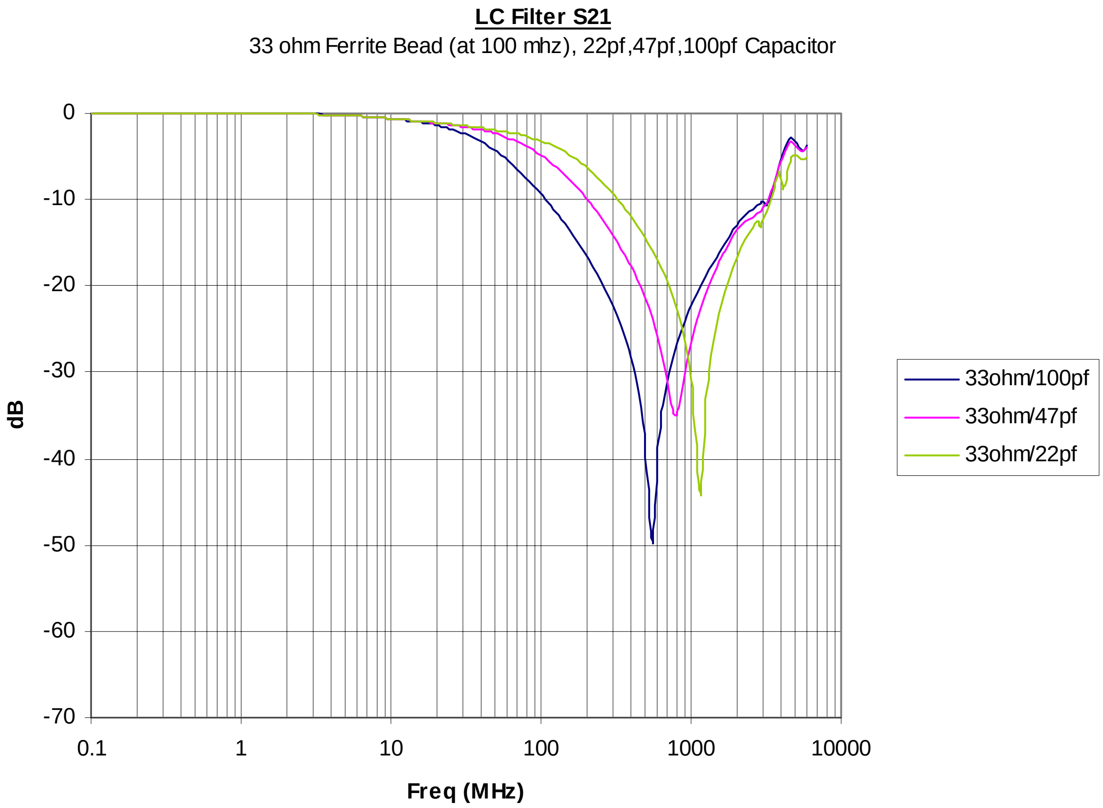
- Pass band ripple can cause a PCB or system to fail EMC requirements. Pass band ripple increases in a high Q LC filters. Although high Q filters have better attenuation in the stop band and a faster roll off rate, they are not typically desired in flex connector attenuation.

- Low Q filters have little or no ripple however have a slower roll off rate and therefore exhibit a decrease in initial stop band attenuation.

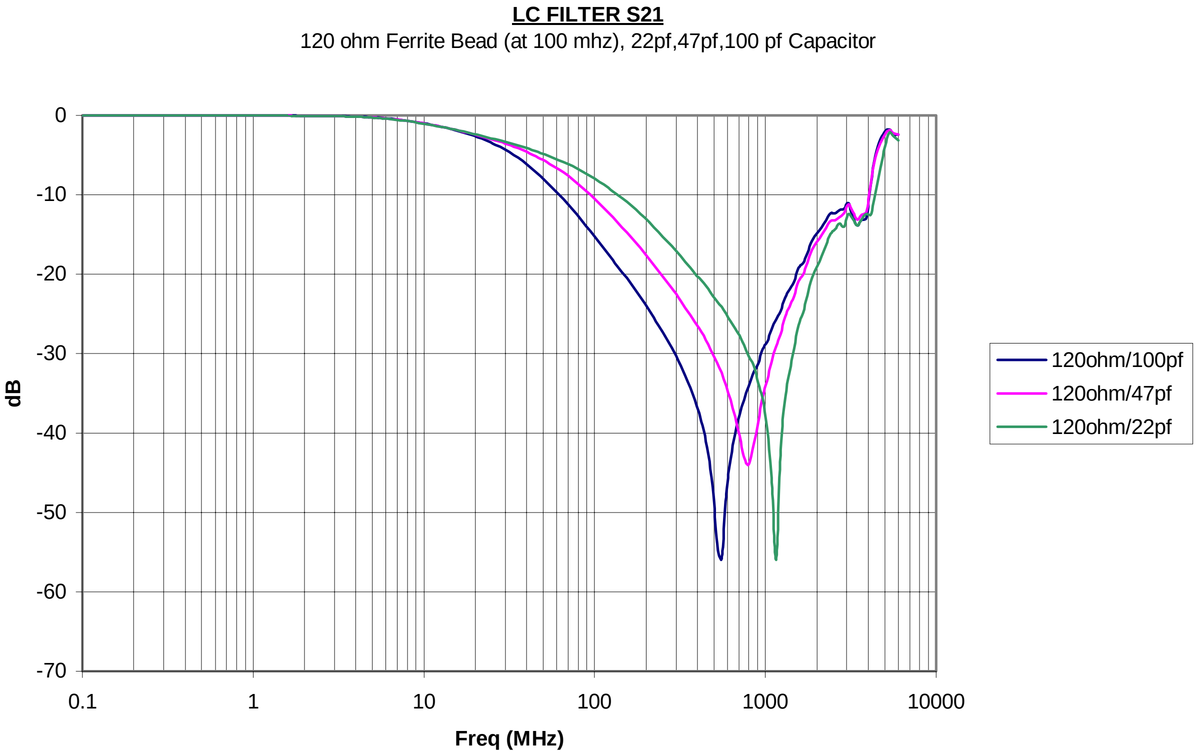
LC Low Pass Filter

Several combinations of Low Pass filters were constructed out of discrete 0603 ferrite beads and capacitors. Initial investigations were done using ferrite beads having 33 ohms of impedance at 100 mhz. This value ferrite bead was connected with three different capacitance values. Capacitance values of 22 pf, 47 pf and 100 pf were chosen to be connected and tested due to their general ability to be used on high speed, medium speed and relatively low speed digital circuitry without causing signal/data skew. Low Pass filter attenuation characteristics desirable for attenuating the 900 mhz and 1800 mhz RF output of the phone were not obtained with the various combinations of these parts.

The decision was made to maintain capacitance values and utilize a ferrite bead having 120 ohms of impedance at 100 mhz. Changing to the higher impedance ferrite bead improved the cut off frequency however did not greatly improve the 1800 mhz attenuation of the filter. Additionally, the size of implementing this filter on a per line basis is relatively large. The LC filter pad layout area is 2.67 mm^2 per line to be filtered. The forward transmission loss test results for the entire component combinations tested is shown in figures 7 a, b.



Discrete LC Filter S21
Figure 7a



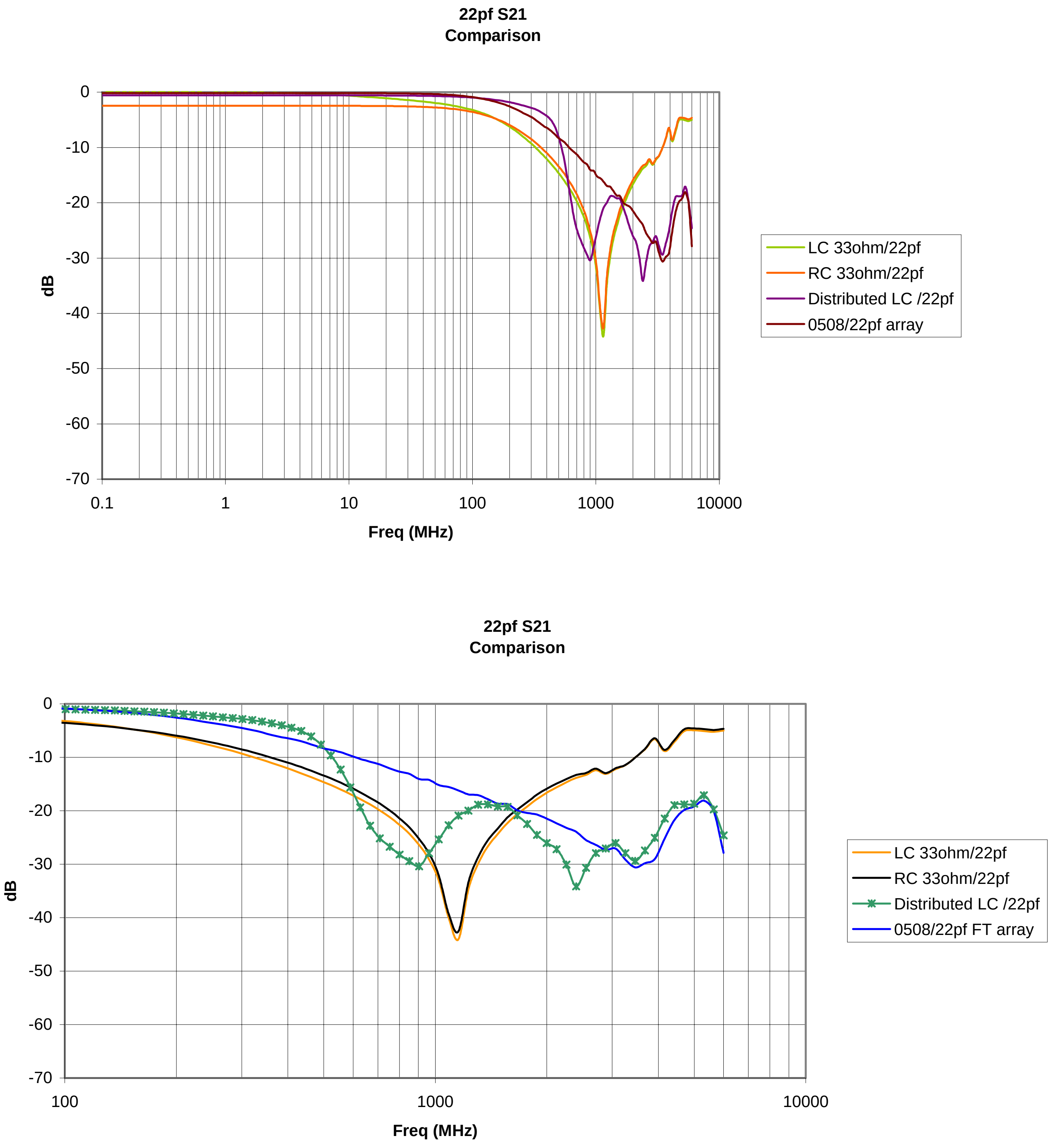
Discrete LC Filter S21

Figure 7b

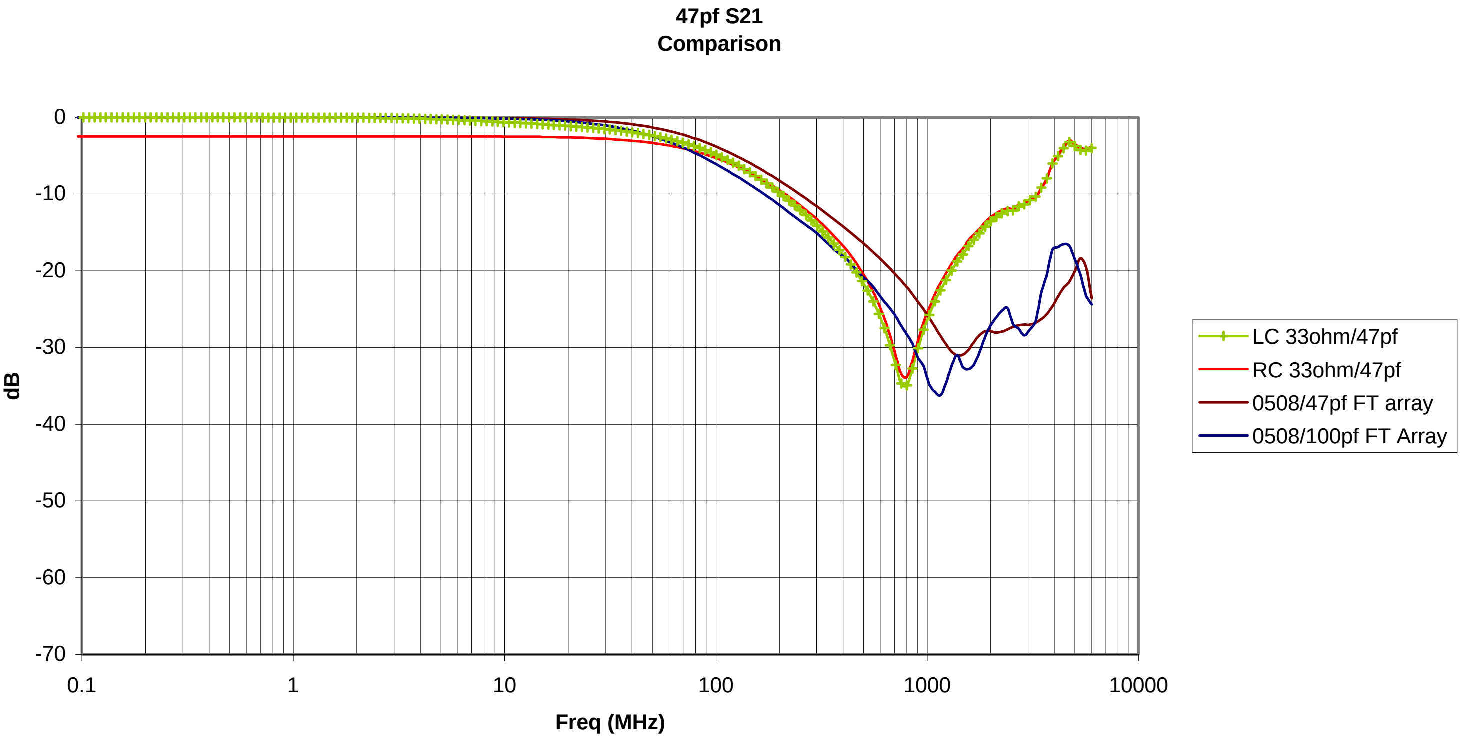
RC Low Pass Filter

Similar capacitance values were used in creating the RC based Low pass filter. These capacitance values are assumed to be fixed and representative for designers working with high speed, medium speed and relatively low speed logic. Resistance values of 33 ohms and 100 ohms were chosen to replace the 0603 ferrite bead. Changing the ferrite beads to resistors created much greater insertion loss for the filter. The levels of insertion loss varied from approximately -2.5 db in the case of the 33 ohm resistor to nearly –6 db for the 100 ohm resistor. Such levels of insertion loss begin to impact circuit operation and power consumption (depending on the particular lines of implementation). Generally speaking 3 db points improved as well as a noted improvement in 900 mhz and 1800 mhz stop band attenuation. The attenuation of 900 mhz and 1800 mhz RF output frequencies of the PA was not yet high enough to prevent overloading and data error on the display.

Though the insertion loss of these RC filters would help low frequency EMI compliance, the RC filters could negatively impact the signal to noise ratio of the flex connector. Additionally the RC discrete filter option is large. The pad layout alone for 0603 elements took up an area of 2.67 mm^2 per line to be filtered. The forward transmission loss test results for the RC filters are compared to LC filters, Distributed LC and modified FeedThrus. This is summarized and shown in figures 8a, b.



RC, LC, Distributed LC and Modified FeedThru Array S21 comparison
Figure 8a



RC, LC, Distributed LC and Modified FeedThru Array S21 comparison
Figure 8b

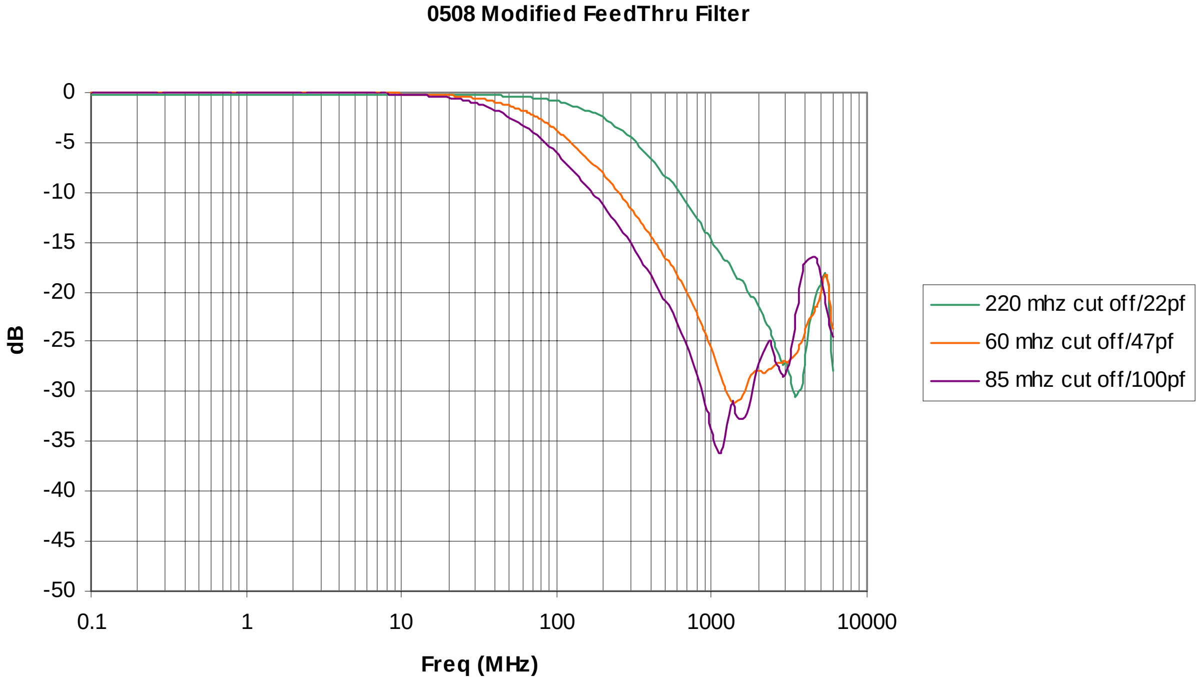
Distributed Filters

Typically, distributed filters are based upon LC, RC or modified FeedThru capacitor designs. Typically, the distributed LC and modified FeedThru capacitor methods are primary candidates for use in flex connector EMI attenuation. Modified FeedThru filter capacitors exhibit many advantages over distributed LC filters.

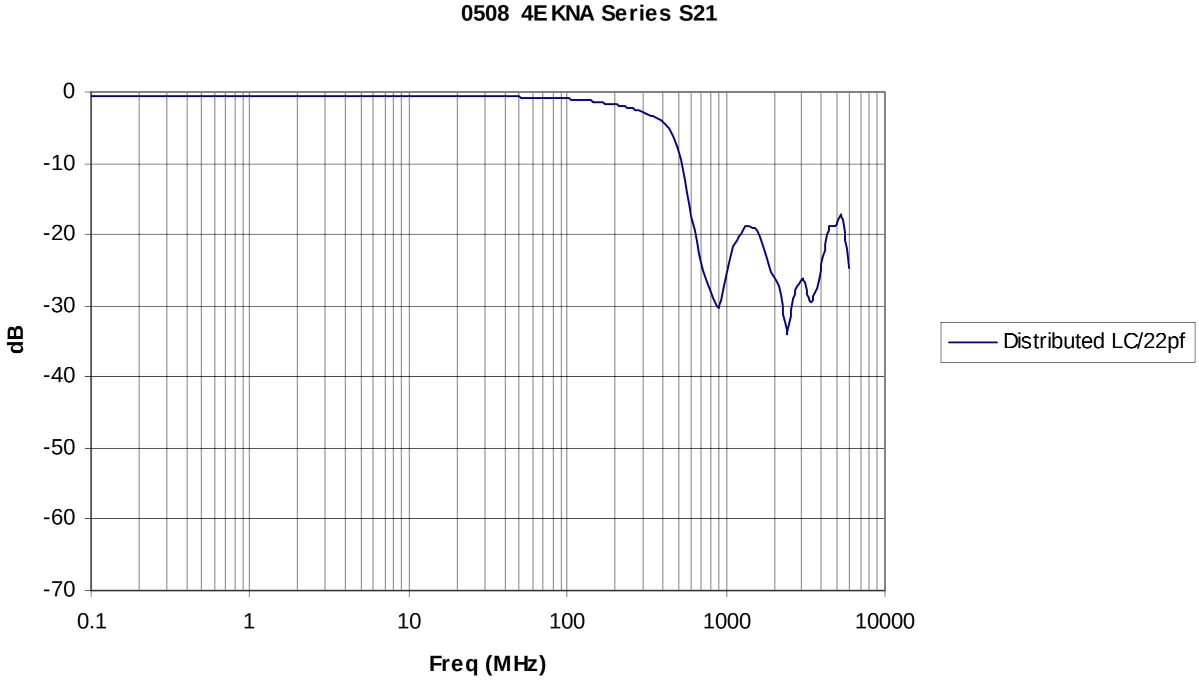
The first advantage Modified FeedThru Filters offer is a lower cross talk between filtered lines than the Distributed LC type filters. Modified FeedThru Filters typically exhibit over -60 db of isolation between filtered lines at 10 mhz and > -20 db of attenuation at 1000 mhz. Distributed LC filters have < -50 db of isolation between filtered lines at 10 mhz and their cross talk increases to –20 db at 1000 mhz.
The low crosstalk of Modified FeedThru Filters yields high isolation between data and driver lines and is therefore ideal to the response of Distributed LC filters.

Modified FeedThru filters also provide a greater value of maximum attenuation then distributed LC filters. The modified FeedThru also has a relatively low Q, which also yields a broad frequency response. For example, this allows a designer to choose a filter that has a high attenuation 900 mhz and 1800 mhz. The additional harmonic content that digital glue logic generated (or the added RF output frequency) is attenuated by the modified FeedThrus broad response.

Some typical S21 filter response curves comparing Distributed LC filter and Modified FeedThru filter response are shown in figures 9 a and b.



Modified FeedThru Filter Forward Transmission Characteristics (S21)
Figure 9a



Distributed LC Filter Forward Transmission Characteristics (S21)
Figure 9b

A general comparison of 3 db points and 20 db pass band is shown in Table 1.

Modified FeedThru	**3db (MHz)**	**20 db (MHz)**	**Max attenuation**	**Loaded Cap**
0508 4 Element Array	220	1665 - 5644	-30db @ 3464 MHz	22 pf
0508 4 Element Array	85	666 - 4996	-30db @ 1474 MHz	47 pf
0508 4 Element Array	60	462 - 3913	-36db @ 1154 MHz	100 pf

Distributed LC	**3db (MHz)**	**20 db (MHz)**	**Max attenuation**	**Loaded Cap**
0508 4 Element Array	320	666 – 1227 1665 - 4422	-34db @ 2402MHz	20 pf

Modified FeedThru	**3db (MHz)**	**20 db (MHz)**	**Max attenuation**	**Loaded Cap**
0612 4 Element Array	260	1780 - 3500	-27db @ 2713 MHz	22 pf
0612 4 Element Array	130	600 – 3400	-28db @ 1570 MHz	47 pf
0612 4 Element Array	60	560 - 3500	-35 db @ 961MHz	100 pf
0612 4 Element Array	30	470 - 3300	-35db @ 2000 MHz	220 pf
0612 4 Element Array	16	220 - 3500	-35db @ 646 MHz	470 pf

Distributed LC	**3db (MHz)**	**20 db (MHz)**	**Max attenuation**	**Loaded Cap**
0612 4 Element Array	154	666 - 1474	-31db @ 904 MHz	35 pf
0612 4 Element Array	129	500 – 1345	-41db @ 1022 MHz	45 pf
0612 4 Element Array	89	410 - 1566	-31db @ 590 MHz	65 pf
0612 4 Element Array	50	270 - 1490	-33db @ 910 MHz	115 pf

Frequency Response comparison Modified FeedThru Filters vs Distributed LC
Table 1

Additionally, the modified FeedThru filters have higher voltage rating and a higher current rating than distributed LC filters. A comparison of parameters such as capacitive loading, voltage rating and current capability are given in Table 2.

Modified FeedThru	**Rated Voltage**	**FeedThru Current**	**Temperature Characteristic**	**3db (MHz)**	**Zi/Zo**
0508 4 Element Array	25 V_{DC}	100 mA	NPO	220	High / High
0508 4 Element Array	25 V_{DC}	100 mA	NPO	85	High / High
0508 4 Element Array	25 V_{DC}	100 mA	NPO	60	High / High

Distributed LC	**Rated Voltage**	**FeedThru Current**	**Temperature Characteristic**	**3db (MHz)**	**Zi/Zo**
0508 4 Element Array	25 V_{DC}	100 mA	NPO	320	High / High

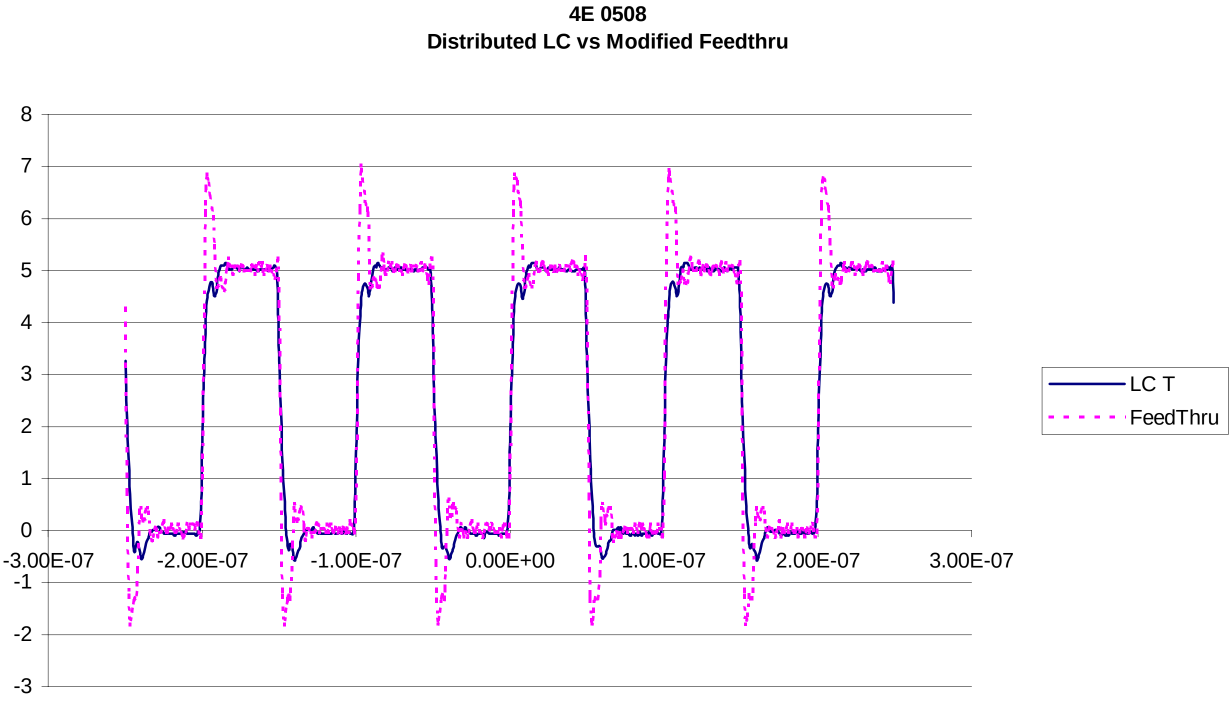
Modified FeedThru	**Rated Voltage**	**FeedThru Current**	**Temperature Characteristic**	**3db (MHz)**	**Zi/Zo**
0612 4 Element Array	100 V_{DC}	300 mA	NPO	260	High / High
0612 4 Element Array	100 V_{DC}	300 mA	NPO	130	High / High
0612 4 Element Array	100 V_{DC}	300 mA	NPO	60	High / High
0612 4 Element Array	50 V_{DC}	300 mA	X7R	30	High / High
0612 4 Element Array	50 V_{DC}	300 mA	X7R	16	High / High

Distributed LC	**Rated Voltage**	**FeedThru Current**	**Temperature Characteristic**	**3db (MHz)**	**Zi/Zo**
0612 4 Element Array	25 V_{DC}	100 mA	NPO	154	High / High
0612 4 Element Array	25 V_{DC}	100 mA	NPO	129	High / High
0612 4 Element Array	25 V_{DC}	100 mA	NPO	89	High / High
0612 4 Element Array	25 V_{DC}	100 mA	NPO	50	High / High

Parametric comparison Modified FeedThru Filters vs Distributed LC
Table 2

Clock Distortion

A comparison of clock distortion when using the distributed LC as well as the modified FeedThru was performed. Test conditions were more controlled than in a cell phone. That is, ideal impedance matching was used and no parasitic loss elements were assumed. This makes for easy and repeatable measurement of clock skew however it increases the potential for ringing (since there is a probably 2 to 5 ohm impedance in many LCD flex connector ribbons & system). Test results no significant data skew with the modified FeedThru structure vs the distributed LCT filter. The distributed LCT filter did offer better performance in attenuating overshoot however it is expected that the performance advantage would not be as great in an actual circuit, which contains parasitic loss elements. The performance summary is shown in Figure 10 below.



Distributed LC T vs Modified FeedThru Filter
Figure 10

Summary

Modified FeedThru filters are an efficient means to filtering LCD flex connectors. The Modified FeedThru Filter takes up 1.56 mm^2 per filtered line vs 2.67 mm^2 as in the case of discrete filter networks. Modified FeedThru Filters use can result in approximately a 48% area reduction in PC board area. The Modified FeedThru filter also yields a constant filtering of lower frequency noise without ripple or poles associated with loaded Q of discrete filters. That makes broadband EMC requirements easier to meet with Modified FeedThru Filters.

Modified FeedThru Filters also exhibit advantages relative to Distributed LC filters.

- Modified FeedThrus are not directional like the Distributed LC filter. That means emission and susceptibility attenuation is symmetrical. From an assembly point of view, no polarity needs to be maintained thus simplifying assembly and eliminating a possible point of board failure.

- Modified FeedThru filters exhibit a lower cross talk between lines. This advantage is approximately >10 db across frequency and is significant since it impacts the signal to noise ratio on a PC board.

- Modified FeedThrus have a higher current carrying capability and operating voltage that Distributed LC Filters. This means designers can enjoy either a large derating factor (thus exponentially benefiting a FIT rate of already sub 1 FIT) or designers can use these devices to create power block filters.

- Modified FeedThrus are a low Q, broadband filter. The 20db filter width is larger than that of distributed LC filters. Many different devices are available to filter a specific frequency spectrum. Different capacitive loading options are available as well.

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