Compact Crossover

Single-channel active constant-voltage crossover filter for single or dual supply voltages

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Features

12dB/octave (40dB/decade) roll-off.
<0.001% THD+N over audio range with OPA2134 amplifiers with 1Vpp signal.
Single or dual supply capable.
Adjustable cutoff frequency.
Small size, 5x5cm.
Input over-voltage and reversal protection.
Support for standard dual OP-AMP packages.
Optional use as purely an audio bandpass filter (4.5Hz to 58kHz).

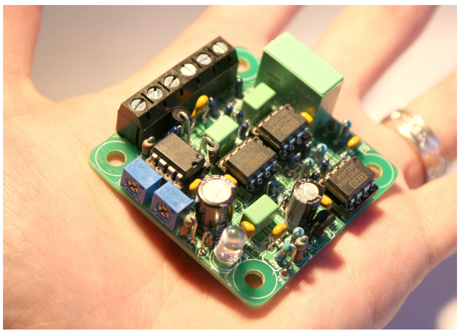
Description

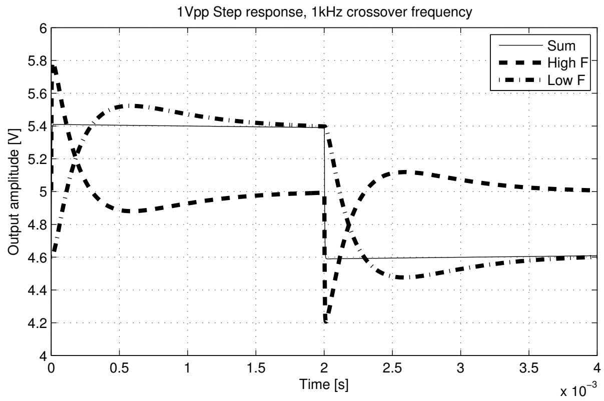
Compact Crossover is a general-purpose active constant-voltage[a] audio crossover filter. By resistor choice the cutoff frequency is effectively arbitrary and maintains a stop-band attenuation of 12dB/octave (40dB/decade). Only through-hole components are used, making it easy to assemble. It is capable of running either from a single supply voltage (10-20V) or a dual supply (±5V to ±10V)[b]. An optional mode, with fewer mounted components, allows it to function as an ultrasonic/infrasonic bandpass filter, passing signals in the audio range (1.5Hz to 58kHz).

[a] Where $V_{out,high} + V_{out,low} = V_{in}$ by design. This is equivalent to a flat phase response and is the only crossover filter type that passes a square wave input signal completely unaltered.

[b] Which can be expanded to 10-30V and ±5 to ±15V by assembly choices.

Overview





High and low frequency outputs and their sum when driven by a square-wave input. Note that the summed outputs exactly equal the input signal.

Contents

Copyright Notice

Hardware Revision History

1.0 Initial version.

Documentation Revision History

1.0 Initial version.

1.0.1 BOM restructured, title page document ID syntax updated.

1.0.2 Title-page photograph added, PCB manufacturing requirements (table 4) added.

1.0.3 BOM restructured.

Absolute Maximum Ratings

PARAMETER	RATING
Constant input voltage, relative to negative supply	22V[a]
Temporary over-voltage	−60Vto +60V[b]
Output short circuit	Unlimited
Input signal voltage (AC)	$V_{-} - 20$V to $V_{+} + 20V$
Input signal voltage (DC)	60V

[a] 36V if input over-voltage protection removed.

[b] Do not keep the device here for extended times (hours), as the input protection stage will eventually fail.

Assembly

Compact Crossover is easy to assemble as there are only through-hole components. See Bill of materials for a list of components to mount, their positions in figure 9, and how to connect to the terminal block in Pin Description. See Operation for a description of how the unit functions as well as how to use operational amplifiers other than OPA2134.

Compact Crossover can be used in several different ways, and depending on this various components are either mounted or left unmounted and solder jumpers are either shorted or left open. It is generally a good idea to first activate any applicable solder jumpers, after which the remaining components can be mounted.

If the device is operated with a power supply below 22V/±11V the over-voltage protection section can be used. Mount F1 and Z1 closely to each other, if possible glue their bodies together with high-temperature tolerant glue to ensure good thermal contact. If operating above this voltage level do not mount Z1. Keep in mind the device will now be unprotected and will likely be damaged should an input over-voltage above 36V occur.

When in crossover filter mode, the crossover frequency must be set by adjusting some resistor and capacitor values. The filter transition frequency is given by

$$f_c = \frac{1}{2\pi R_f C_f}$$
$$\therefore R_f = \frac{1}{2\pi f_c C_f}$$

where $R1, R2, R3, R8, R10, R11, R12 = R_f$, $R7, R9 = \frac{R_f}{4}$, $C2, C3, C4 = C_f$. At frequencies above f_c most of the signal power will be in the “high” output, and at frequencies below f_c most of the signal power will be in the “low” output. For example, if $f_c = 2kHz, C_f = 2.4nF$ then $R1, R2, R3, R8, R10, R11, R12 = 33k\Omega$ and $R7, R9 = 8.2k\Omega$.

When selecting filter capacitors be sure to use plastic film capacitors or NP0/C0G dielectric ceramic capacitors, with at worst 5% tolerance, preferably 2% or better tolerance. When selecting resistors be sure to use metal film 1% resistors.

Assembly for the operation modes is listed below, a matrix listing the valid and invalid combinations of modes are shown in table 1.

Single supply mode The standard operating mode, this should be used when there is only a unipolar power source available (V_+ and ground). In this case, mount all internal biasing components in the dashed region shown in figure 9 and **do not short SJ5**. (Note: keep in mind R24 is in a separate group).

Dual supply mode Use this mode when a bipolar power source is available (V_+, V_-, and ground). In this case, do not mount C10,C11,R16,R20,R22,R24,VR1 as shown in figure 9 and **ensure that SJ5 is shorted**. (Note: these components are all enclosed by the dashed lines on the PCB, keep in mind R24 is in a separate group).

Crossover filter mode The standard operating mode, this activates both the input pre-filter and the crossover filter. Mount all crossover filter components as per figure 9 and **do not short SJ3, SJ4**. (Note: These are all marked with a circle on the PCB).

Infrasonic/ultrasonic filter A bare-bones mode, where the device is only used to block and DC/infrasonic and ultrasonic disturbances from the signal. Do not mount any of R1-R15,C1-C6,IC1-IC3 and **ensure that SJ3,SJ4 are shorted**.

Low impedance output Default: OFF. Enable to directly drive the output from the operational amplifiers (which normally driven through a 100Ω resistor). **Only use this when needed**, this raises the risk of oscillation due to capacitive loading. Do not mount R4,R13 and **ensure that SJ1,SJ2 are shorted.**

Common ground mode Default: OFF. Enable to force the signal ground and power ground together when in single supply mode. In typical operation, the signal ground and power ground (the ground used for operational amplifiers) are separated, improving the power supply rejection ratio of the circuit. This does however result in a positive DC current through the signal ground connector which is

$$\frac{V_+ - V_{bias}}{R16} = \frac{V_+ - 5V}{1800\Omega} = \begin{matrix} \underbrace{3.8mA}_{V_+=12V} \\ \underbrace{8.3mA}_{V_+=20V} \end{matrix}$$

when in single supply mode that leaves the crossover filter and enters the next stage (typically a power amplifier). For nearly all purposes the device receiving the outputs from the crossover filter will tolerate this current in the signal ground, though if some particularly sensitive hardware is used it is possible to allow this current to instead pass through the power ground connection by activating this mode. This will however reduce the PSRR significantly and allow for the potential for ground loops. Note that if the next stage (e.g. the power amplifier) has an infinitely high impedance input the signal ground will only rise

$$R24\frac{V_+ - V_{bias}}{R16} = \frac{V_+ - 5V}{18} = \begin{matrix} \underbrace{380mV}_{V_+=12V} \\ \underbrace{830mV}_{V_+=20V} \end{matrix}$$

Table 1: Matrix of combinations of operating modes.

	Single supply	Dual supply	Crossover filter	Infrasonic / ultrasonic filter	Low impedance output	Common ground
Single supply	X	**INVALID**	VALID	VALID	VALID	VALID
Dual supply		X	VALID	VALID	VALID	**INVALID**
Crossover filter			X	**INVALID**	VALID	VALID
Infrasonic / ultrasonic filter				X	VALID	VALID
Low impedance output					X	VALID
Common ground						X

above the power ground signal, which is typically completely safe. To enable, do not mount C12,R24 and **ensure that SJ6 is shorted**. **Note that this mode can not be used in dual supply mode**, and furthermore would not be needed as there is no current sinked into the signal ground cable. See more about this mode in Operation.

Pin Description

Connections to the unit are all made through the terminal block X1 as follows;

<table>
<tr><th>Pin</th><th colspan="2">Description (mode dependent)</th></tr>
<tr><td>INPUT</td><td colspan="2">Line-level analog signal input (all modes).</td></tr>
<tr><td rowspan="2">HIGH</td><td>Crossover mode</td><td>Infrasonic/ultrasonic filter mode</td></tr>
<tr><td>High-frequency component of line-level analog signal output.</td><td rowspan="3">Line-level signal output. The two output terminals are identical.</td></tr>
<tr><td rowspan="2">LOW</td><td>Crossover mode</td></tr>
<tr><td>Low-frequency component of line-level analog signal output.</td></tr>
<tr><td>V+ IN</td><td colspan="2">Connect to positive DC power supply voltage (all modes).</td></tr>
<tr><td rowspan="2">SIG GND</td><td>Common ground mode off</td><td>Common ground mode on
(Note; only applicable to single-supply mode).</td></tr>
<tr><td>Single supply mode;
Reference ground level for signal input and output.
Connect to ground conductor for input/output signal.
Dual supply mode;
Connect to power ground.</td><td>Identical to power supply ground.
Connect to ground conductor for input/output signal.</td></tr>
<tr><td rowspan="2">PWR GND /
V- IN</td><td>Single supply mode</td><td>Dual supply mode</td></tr>
<tr><td>Connect to power supply ground conductor.</td><td>Connect to power supply negative voltage.</td></tr>
</table>

Usage

Compact Crossover is intended to be used as a component as part of an larger amplifier system – together with a power amplifier, power supply, and so on. Due to this there are many different ways of assembling and configuring the device as listed in Assembly. A description of how to connect the unit in any of the modes available is listed in Pin Description. An example of one way of using Compact Crossover is shown in figure 1.

The potentiometers R5 and R14 can be used to adjust the balance of the outputs. Typically tweeter loudspeakers will have a higher sensitivity [dB/W] than woofer or midrange loudspeakers. To compensate for this effect and maintain an even audio amplitude over the frequency range, connect Compact Crossover to the system it is intended for and adjust R5 and R14 until a balanced sound image is achieved[1]. Be sure to keep one of R5 and R14 at no attenuation (maximum volume) to maintain the highest SNR.

Compact Crossover's summed outputs are virtually completely in phase with the input signal – the output is neither inverted nor noticeably delayed in the audio range.

In general, as the power draw is low there is no need to use cables with a high conductor cross section. Be sure to use well shielded cables for the signal input and output. As the power draw is low, there is no need to heat-sink the device. Keep in mind that during operation the operational amplifiers will become warm to the touch, this is completely normal behavior.

It is very important to keep in mind that when operating **in single-supply mode the output from the device will be biased around 5V**[2]. This is typically not a problem for the device that is connected to the filter's output, as input stages to audio parts will nearly always AC-couple their inputs, but it is important to check to make sure this is the case. One way to do this is to connect a lab power supply set to zero volts through a $1k\Omega$ resistor to the input of the device to be used with Compact Crossover's output, measure the voltage output from the device, and slowly raise the voltage to 5V. If the output voltage does not rise the input is AC coupled and can be used with Compact Crossover. **If connected to a device that does not AC couple the input there is a danger of severely distorting the signal, possibly even damaging the attached device!**

Another important factor to consider when in single-supply mode that output will rise from 0V to a 5V bias during an initial startup transient time. This is controlled by the value of R16 and C10, and is for all allowable supply voltages (as in Electrical Characteristics) less than 10ms. Most power amplifier stages will mute the output during startup, if not this will result in a loud pop on startup.

[1] Or, alternatively, feed a pure sinusoidal signal at the crossover frequency to the input of Compact Crossover. Adjust R5 and R14 until both outputs sound equally loud, alternately measure the SPL from each loudspeaker and adjust R5 and R14 until both loudspeakers output an equally loud sinusoid.

[2] The output from the device will be a 5V DC offset, with an AC signal superimposed

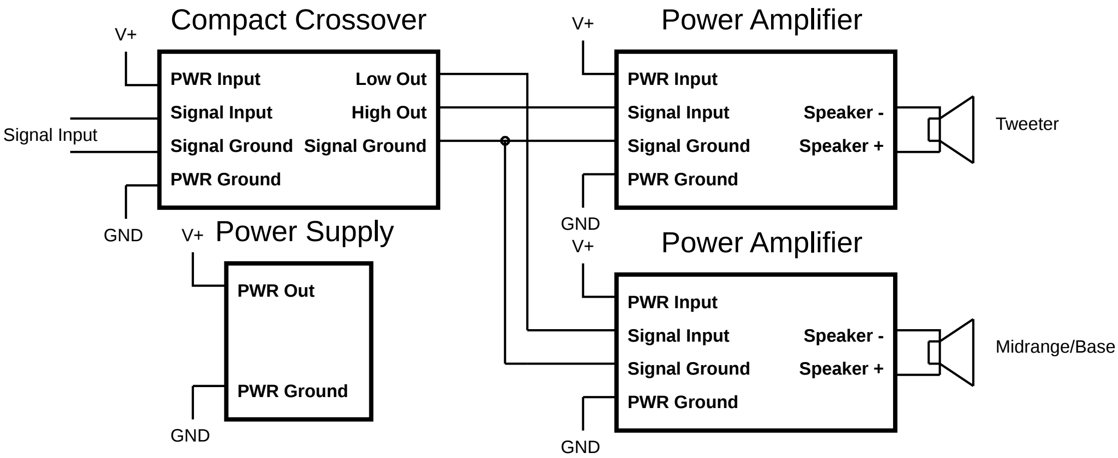


Figure 1: Example application of Compact Crossover here with a mono signal input and driving two single-supply amplifiers.

Bill of materials

Note; The values listed below for the filter capacitors and filter resistors are for a crossover frequency of $2kHz$; for other crossover frequencies see Assembly. The suggested part number is only that — a suggestion — and may be replaced with any other equivalent matching the specifications listed under value, rating, and type. Additionally, a value of 4n7 corresponds to a value of 4.7n, and in the case of a capacitor corresponds to 4.7nF.

COMPONENT NAME	VALUE	RATING	TYPE	SUGGESTED PART NO.
C1,C5,C6,C7,C11,C12	100n	50V or better, X5R or better	2.5x7.5mm, 5mm pin grid	K104K15X7RF5TH5
C2,C3,C4	C_f	50V or better, NP0/C0G or film	7.5x7.5mm, 5mm pin grid	Filter capacitor, see Assembly
C8	1u	100V or better, film	8.5x18mm, 15mm pin grid	MKT1820510255
C9	330p	50V or better, NP0/C0G	2.5x7.5mm, 5mm pin grid	C317C331J1G5TA
C10	10u	50V or better, electrolytic	6.3mm can, 2.5mm pin grid	100YXF10MEFC6.3X11
C13	100u	50V or better	8mm can, 3.5mm pin grid	50ZLH100MEFC8X11.5
D1	1N4001	Generic 1A, 50V diode	DO-41 package	1N4001
F1	100mA PTC fuse	50V, $I_{hold} \geq 100mA$, $I_{trip} \leq 200mA$	3.5x7.5mm, 5.1mm pin grid	MC36184
IC1,IC2,IC3,IC4	OPA2134P	Generic dual OP-AMP with standard pinout and $V_{Supply,max} \geq 36V$	DIL08 package	OPA2134PA
LED1	Power OK LED	Any generic 20mA LED	5mm body, 2.5mm pin grid	L-53LGD
R1,R2,R3,R8,R10,R11,R12	R_f	1/4W, 1%	2.5mm body	Filter resistor, see Assembly
R4,R13,R24	100R	1/4W, 5%	2.5mm body	MF25 100R
R5,R14	10k - 20k	Generic cermet trimmer, 10%		3362W-1-103LF
R6,R15,R16	1k8	1/2W, 5%	3.5mm body	SFR16S0001801JA500
R7,R9	$\frac{R_f}{4}$	1/4W, 1%	2.5mm body	Filter resistor, see Assembly
R17,R19,R20,R21,R22	33k	1/4W, 1%	2.5mm body	MF25 33K
R18,R23	8k2	1/4W, 1%	2.5mm body	MF25 8K2

COMPONENT NAME	VALUE	RATING	TYPE	SUGGESTED PART NO.
SJ1,SJ2	JUMPER			Short when in low impedance mode
SJ3,SJ4	JUMPER			Short when in infrasonic/ultrasonic mode
SJ5	JUMPER			Short when in bipolar supply mode
SJ6	JUMPER			Short when in common ground mode
TP1				Test pad for internal bias
VR1	TL431C	2%, generic TL431	TO92	TL431ACZ-AP
X1			5mm x 6-way terminal	CTB5202/6
Z1	SA22A	Generic 500W TVS Zener	DO-15	SA22A

Mechanical Description

Compact Crossover consists of a PCB and associated through-hole components, with a finished size of 50x50mm and a build height of 18 mm (limited by the input AC-coupling capacitor C8 and the input decoupling capacitor C13). Mounting holes are listed in table 5, with the reference frame shown in figure 2. PCB manufacturing requirements are shown in table 4, and should generally be achievable at any PCB house.

As the power draw is low, there is no need to heat-sink the device. Keep in mind that during operation the operational amplifiers will become warm to the touch, this is completely normal behavior.

Table 4: PCB manufacturing requirements.

PARAMETER	REQUIREMENT	UNIT
PCB thickness	Any (nominal 1.6)	mm
PCB layers	2	-
Copper fill thickness/density (tested)	35/1	µm / oz/ft^2
Trace isolation (minimum)	0.2032/8	mm/mil
Trace width (minimum)	0.254/10	mm/mil
Trace to board edge (minimum)	0.25	mm
Drill to board edge (minimum)	0.4532	mm
Drill diameter (minimum)	0.3	mm
Via annular ring (minimum)	0.2032/8	mm/mil

Table 5: Mounting hole locations.

HOLE DIAMETER [mm]	POSITION X [mm]	POSITION Y [mm]
4.1	5	5
4.1	5	45
4.1	45	5
4.1	45	45

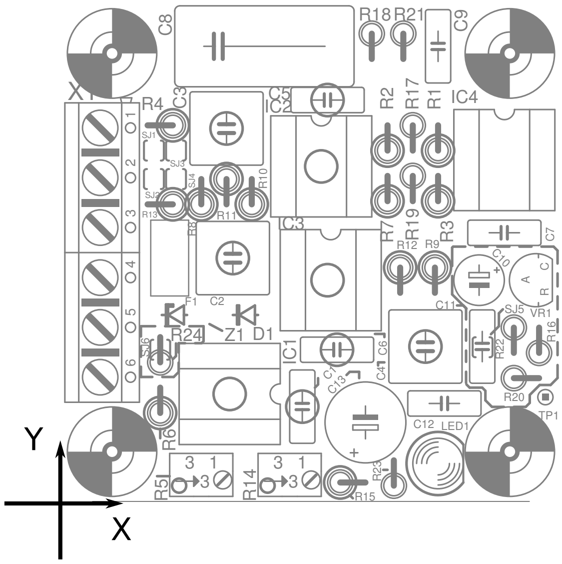


Figure 2: Coordinate system for mounting holes.

Electrical Characteristics

$V_{in} = 20$V, in single supply mode unless otherwise specified.

PARAMETER	SYMBOL	TEST CONDITIONS/COMMENTS	MIN	TYP	MAX	UNIT
Input Characteristics						
Power Input voltage	V_{in}	Single supply mode	10		22[3]	V
Power Input voltage	V_{in}	Dual supply mode	±5		±11[4]	V
Input impedance	Z_{in}			41//330		kΩ//pF
Quiescent supply current		Crossover filter mode, high-impedance load		42		mA
Quiescent supply current		Ultrasonic/infrasonic filter mode, high-impedance load		20		
Output Characteristics						
THD plus noise		$V_{in} = 1$Vpp, over audio range, OPA2134 amplifiers used			0.001	%
Output impedance		Low impedance mode disabled		100		Ω
Output impedance		Low impedance mode enabled		0.01		Ω
Short circuit current				±40		mA
Output voltage offset		Single supply mode		5		V
Device parameters						
Bias voltage	V_{bias}	Single supply mode		5		V
Net gain		Outputs summed, at 1kHz		-2		dB
Dynamic behavior						
Infrasonic cutoff frequency		$-3dB$ point, single pole filter[5]		4.8		Hz
Ultrasonic cutoff frequency		$-3dB$ point, single pole filter[6]		58		kHz
Infrasonic/ultrasonic stop-band attenuation		Single pole filter		20		dB/dec
Crossover filter stop-band attenuation		Dual pole filter		40		dB/dec
Power supply rejection ratio[7]	PSRR	If common ground mode disabled		85		dB
Bias settling time to 0.1% on startup		$V_{supply} > 10V$		15		ms

[3]Can be up to 36V if input over-voltage protection removed, see Operation
[4]Can be up to ±18V if input over-voltage protection removed, see Operation
[5]Cutoff frequency controlled by $f_{-3dB} = \frac{1}{2\pi C_6(R_{21}+R_{18})}$
[6]Cutoff frequency controlled by $f_{-3dB} = \frac{1}{2\pi C_9 R_{18}}$
[7]Assuming 0.1Ω impedance from Compact Crossover signal ground to next stage's signal ground.

Typical Performance

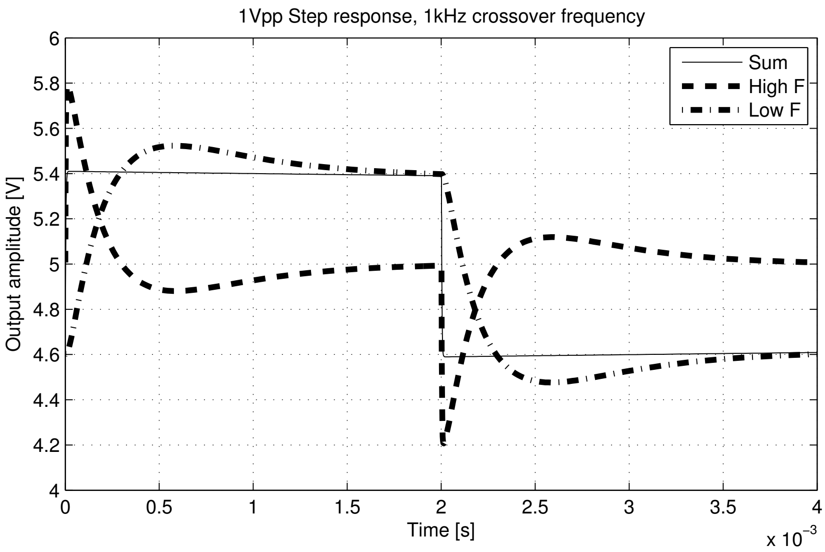


Figure 3: System output to a $1V_{pp}$ step input, when configured as a crossover filter with a crossover frequency of 1kHz operating from a single supply voltage.

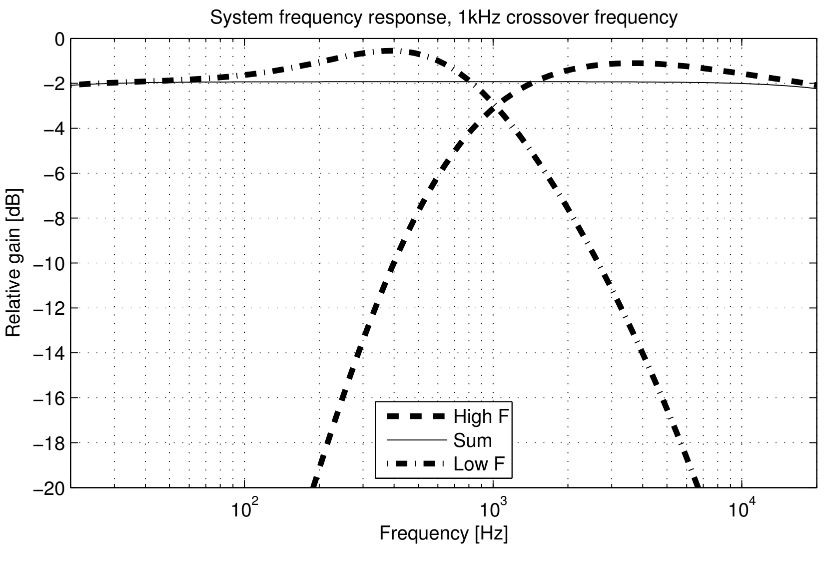


Figure 4: AC analysis of system near crossover frequency, crossover frequency set to 1kHz. The output asymmetry is due to the ultrasonic filter's (small) attenuation at audio frequencies.

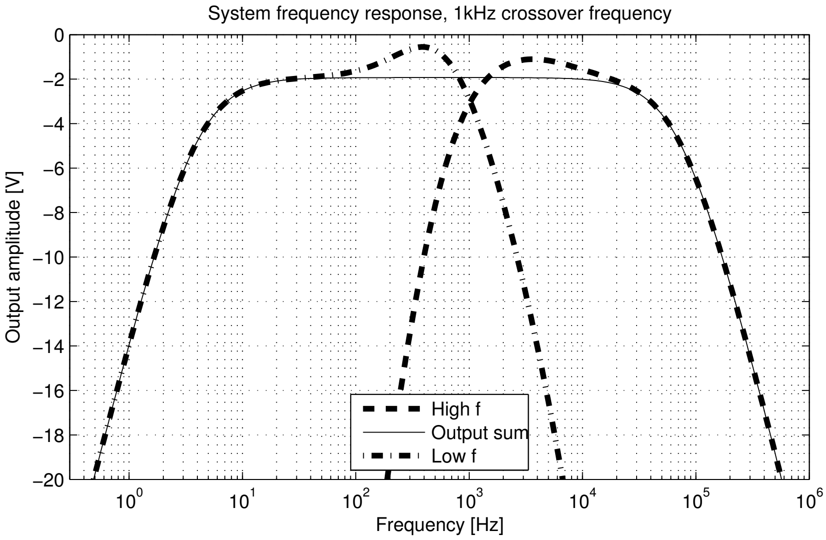


Figure 5: AC analysis of system rejection of infrasonic and ultrasonic frequencies with a crossover frequency of 1kHz.

Operation

Compact Crossover is a purely analog crossover filter heavily based on National Semiconductor's Application Note 346 – High-Performance Audio Applications of LM833[8]. This application note lists (among others) a constant-voltage generic active crossover network. Additionally, Compact Crossover consists of an input infrasonic/ultrasonic filter, internal bias generation, and input over-voltage/reverse polarity protection. From a signal propagation point of view, the circuit functions as follows;

A signal applied to terminal 1 on the terminal block is high-pass filtered by C8 and R18/R21 to a cutoff frequency of

$$f_{HP} = \frac{1}{2\pi C_8 \left(R_{21} + R_{18}\right)} \underset{typ.}{\approx} 4.8\text{Hz}$$

and low-pass filtered by R18 and C9 to a cutoff frequency of

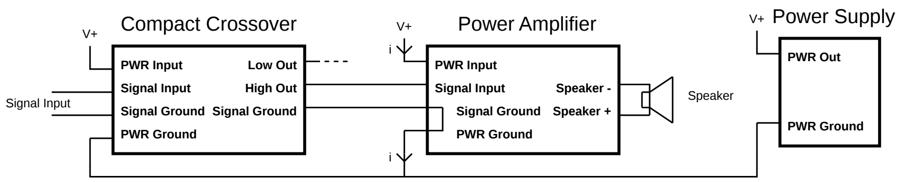
$$f_{LP} = \frac{1}{2\pi R_{18} C_9} \underset{typ.}{\approx} 58\text{kHz}.$$

The signal is biased around OPAMP_BIAS (typically 5V) through R21, supplying IC4A (and all other amplifiers) with a signal that lies within it's linear range. The signal is then inverted with unity gain through IC4B, which counteracts an inversion the crossover filter section will generate later in order to ensure the device's output maintains the same phase as the input (so that the high and low frequency outputs as well as the input signal can be used together for situations that may require this). This generates the signal labeled CONDITIONED, which is fed into the crossover network.

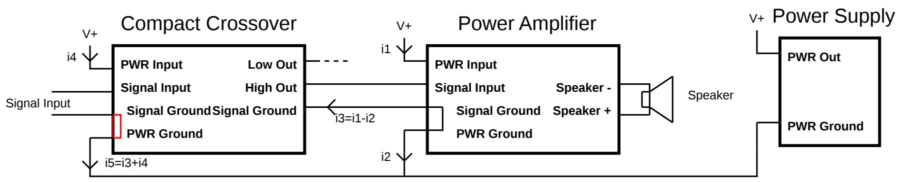
The crossover network is identical to the network shown in the previously noted application note, which generates a low-frequency and high-frequency signal which when summed exactly equal the input to the crossover network. These signals are fed into identical attenuation stages consisting of R5/R6 and R14/R15, which allow for adjusting the relative gain of each stage to compensate for loudspeaker sensitivity differences. IC1A and IC1B simply buffer the signal, which is then passed through a R4 and R13, and then output to the terminals HIGH_OUT and LOW_OUT. Note that shorting SJ1 and SJ2 allows for the removal of the output resistor, which otherwise functions to stabilize the output in the presence of capacitive load (which may otherwise cause IC1A/IC1B to oscillate). If the output from the filter is close to the next stage's input these may be shorted.

When operating in single supply mode the internal bias generator creates a 5V bias for the operational amplifiers to work around, giving headroom to ensure the devices are kept in their linear range. The OPA2134 amplifiers have a specified common mode input range that reaches 2.5V above the negative supply voltage, making it possible to drive signals up to 2Vpp (which would then be internally biased to a signal of 5 ± 1V; as the crossover filter has a gain of +3dB near the crossover frequency this will result in an output of 5 ± 2V for some frequencies, leaving 500mV of headroom to the negative

[8] 2002 National Semiconductor Corporation, http://www.national.com



(a) Isolation of signal ground and power ground eliminates ground loops.



(b) Non-isolated signal ground and power ground leads to ground loop.

Figure 6: The isolation of signal ground and power ground is required to remove ground loops.

supply). It is safe to alter the ratio of R17/R19 to alter the total gain. If so ensure that $1k\Omega < R17, R19 < 33k\Omega$ and that the input signal does not cause the internal network to leave it's linear operating region.

The use of a precision zener reference (VR1) raises the power supply rejection ratio greatly, and is on the order of 85dB. As the positive supply is heavily decoupled with a 100uF capacitor and the input PTC fuse has a minimum resistance of 2.5Ω this gives an additional degree of attenuation at high frequencies.

In single supply mode there is also a distinction between *power ground* – where current that flows out from the negative supply pin on the operational amplifiers is sinked – and *signal ground* – the reference level for the input and output signals. If this distinction is not made there is the potential for ground loop interference. This is illustrated in figure 6, where in figure 6a power ground and signal ground are kept separate in Compact Crossover. This ensures there is no undesired current flow through the signal ground conductor. In figure 6b however signal ground and power ground are not isolated. This creates the potential for current from the power amplifier to flow through the signal ground connection and then return through the power ground connection, caused by the nonzero resistance from the power ground terminal in the power amplifier to the shared grounding point. Compact Crossover does not completely separate the two grounds, they are connected with C12 and R24 (typically 100Ω and 100nF), which is done to reduce EMI susceptibility, as well as act as a failsafe should the signal ground connector loosen from the power amplifier. From a ground-loop perspective this impedance is far higher than any connection resistance, reducing the potential ground loop current to an insignificantly small amount.

Finally, as the 5V bias voltage generated by VR1 is referenced to signal ground, there is a constant parasitic current that must be sinked by the device Compact Crossover is connected to. This currently is relatively small, and is given by

$$\frac{V_+ - V_{bias}}{R16} = \frac{V_+ - 5V}{1800\Omega} = \underbrace{3.8mA}_{V_+=12V} \ \underbrace{8.3mA}_{V_+=20V} .$$

If this current is not absorbed by the next stage (such as if the signal ground input is of high impedance) the signal ground level voltage will rise relative to power ground. This is limited by R24 and is given by (in the extreme case of an infinitely high impedance)

$$R24\frac{V_+ - V_{bias}}{R16} = \frac{V_+ - 5V}{18} = \underbrace{380mV}_{V_+=12V} \ \underbrace{830mV}_{V_+=20V} ,$$

which is for all but the most extreme cases safe. If this is not the case, then SJ6 can be shorted, which connects the two ground levels internally. This will result in no voltage difference between the two ground levels locally, but may result in a ground loop current as shown in figure 6b. This is not recommended unless absolutely needed as this reduces the PSRR greatly.

When Compact Crossover is used in infrasonic/ultrasonic filter mode, the solder jumpers SJ3 and SJ4 are shorted, thereby removing the effects that the crossover filter section would have (the components should then not be mounted).

When in dual-supply mode, the internal bias section is unneeded and effectively removed by shorting SJ5 (and not mounting the unneeded components).

The input over-voltage protection consists of F1 and Z1. At low to moderate overvoltage levels the power dissipation in Z1 heats up F1, increasing the resistance in F1 and eventually triggering the fuse. At higher levels the fuse triggers itself rapidly, and remains in its triggered state until it cools down, for example through a power cycle.

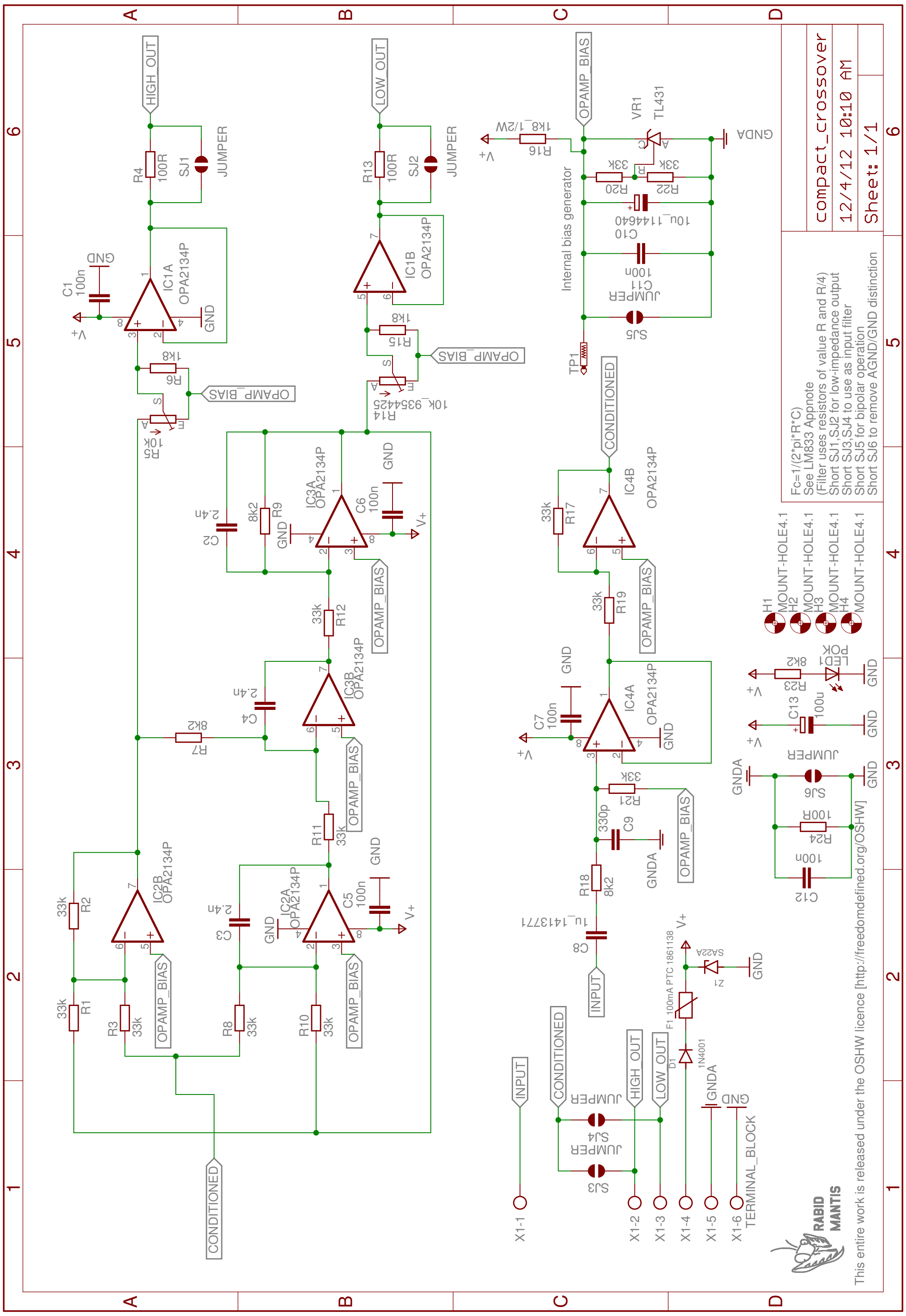
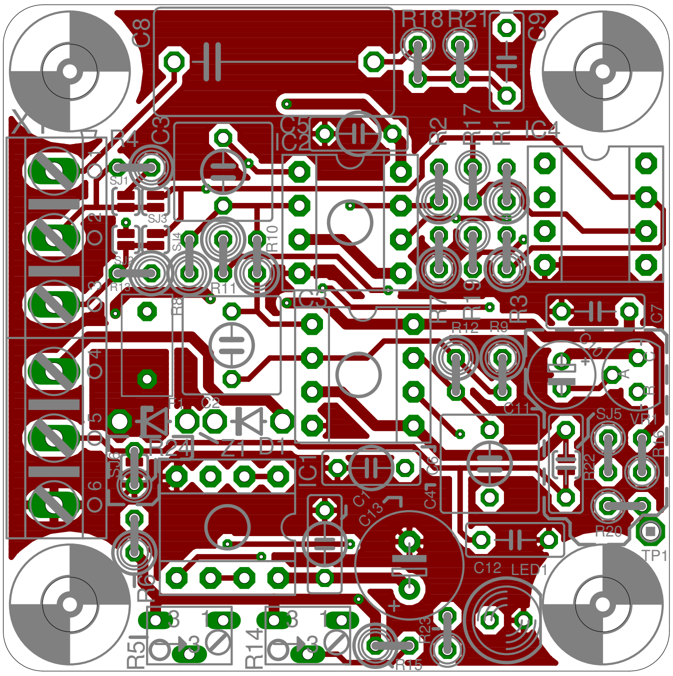
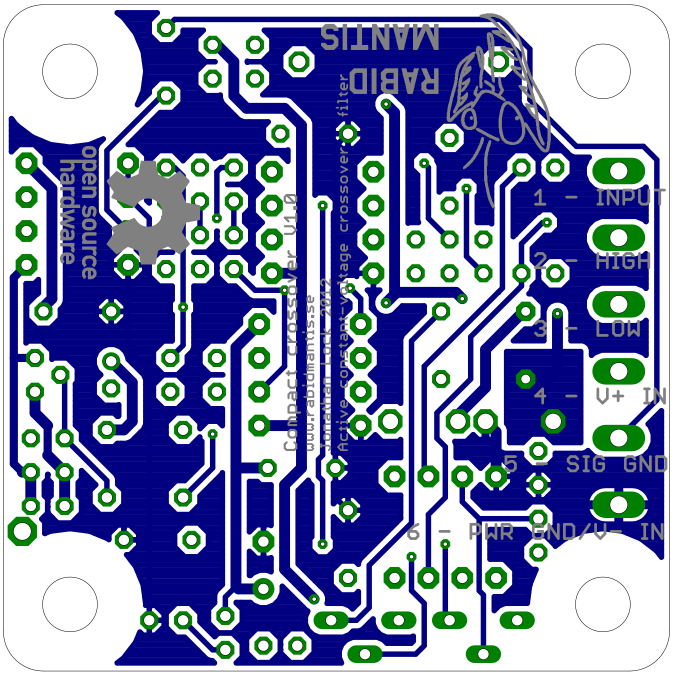


Figure 7: Full schematic for Compact Crossover.

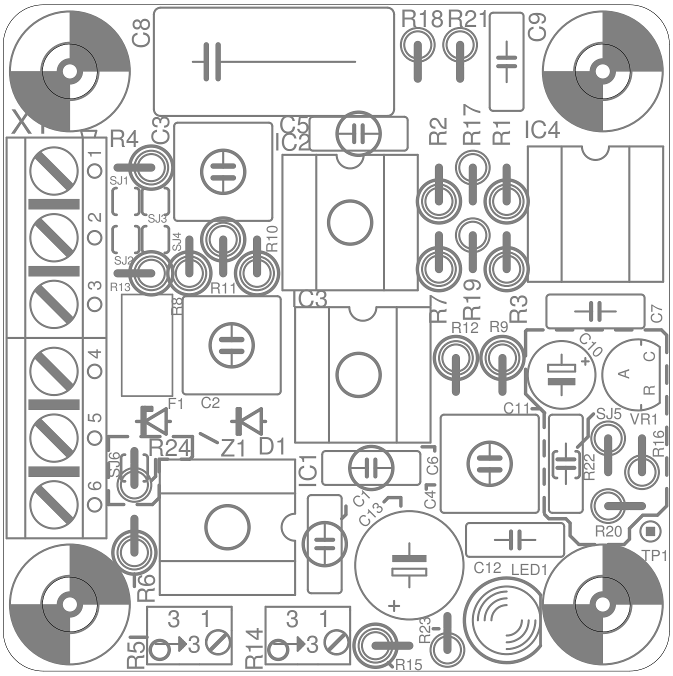


(a) Complete top layer as seen from above.

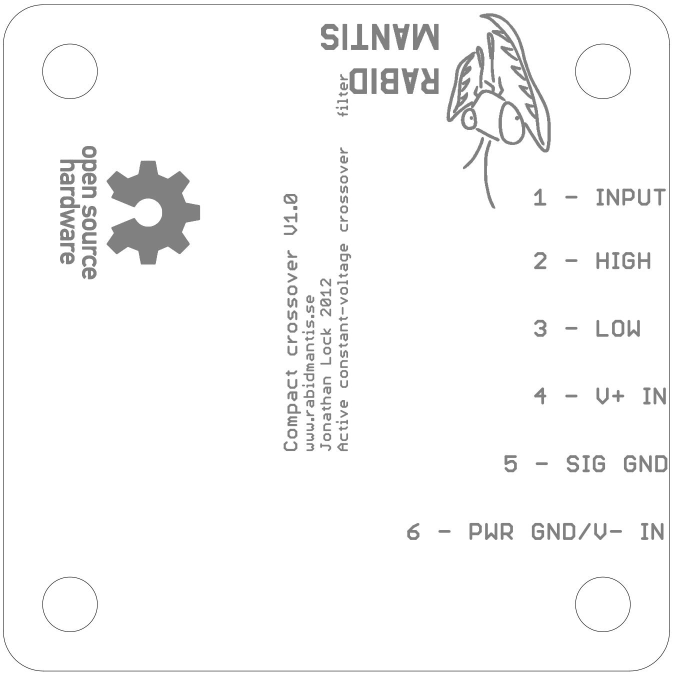


(b) Complete bottom layer as seen from below.

Figure 8: PCB details.



(a) Top layer component outline as seen from above.



(b) Bottom layer component outline as seen from below.

Figure 9: Component placement details.