UNIVERSAL ACTIVE FILTER

Check for Samples: UAF42

FEATURES

- **VERSATILE:**
  - **Low-Pass, High-Pass**
  - **Band-Pass, Band-Reject**
- **SIMPLE DESIGN PROCEDURE**
- **ACCURATE FREQUENCY AND Q:**
  - **Includes On-Chip 1000pF ±0.5% Capacitors**

APPLICATIONS

- **TEST EQUIPMENT**
- **COMMUNICATIONS EQUIPMENT**
- **MEDICAL INSTRUMENTATION**
- **DATA ACQUISITION SYSTEMS**
- **MONOLITHIC REPLACEMENT FOR UAF41**

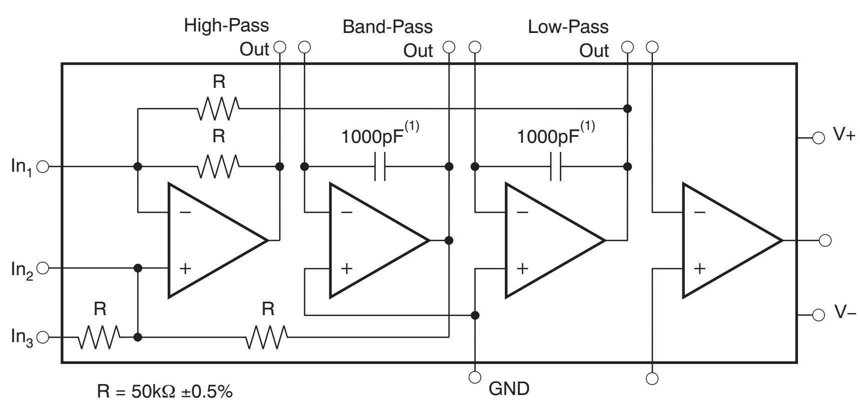
DESCRIPTION

The UAF42 is a universal active filter that can be configured for a wide range of low-pass, high-pass, and band-pass filters. It uses a classic state-variable analog architecture with an inverting amplifier and two integrators. The integrators include on-chip 1000pF capacitors trimmed to 0.5%. This architecture solves one of the most difficult problems of active filter design—obtaining tight tolerance, low-loss capacitors.

A DOS-compatible filter design program allows easy implementation of many filter types, such as Butterworth, Bessel, and Chebyshev. A fourth, uncommitted FET-input op amp (identical to the other three) can be used to form additional stages, or for special filters such as band-reject and Inverse Chebyshev.

The classical topology of the UAF42 forms a time-continuous filter, free from the anomalies and switching noise associated with switched-capacitor filter types.

The UAF42 is available in 14-pin plastic DIP and SOIC-16 surface-mount packages, specified for the –25°C to +85°C temperature range.



NOTE: (1) ±0.5%.

Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this data sheet.

This integrated circuit can be damaged by ESD. Texas Instruments recommends that all integrated circuits be handled with appropriate precautions. Failure to observe proper handling and installation procedures can cause damage.

ESD damage can range from subtle performance degradation to complete device failure. Precision integrated circuits may be more susceptible to damage because very small parametric changes could cause the device not to meet its published specifications.

ABSOLUTE MAXIMUM RATINGS(1)

Over operating free-air temperature range unless otherwise noted.

	UAF42	UNIT
Power Supply Voltage	±18	V
Input Voltage	$\pm V_S \pm 0.7$	V
Output Short-Circuit	Continuous	
Operating Temperature	–40 to +85	°C
Storage Temperature	–40 to +125	°C
Junction Temperature	+125	°C

(1) Stresses above these ratings may cause permanent damage. Exposure to absolute maximum conditions for extended period may degrade device reliability. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those specified is not supported.

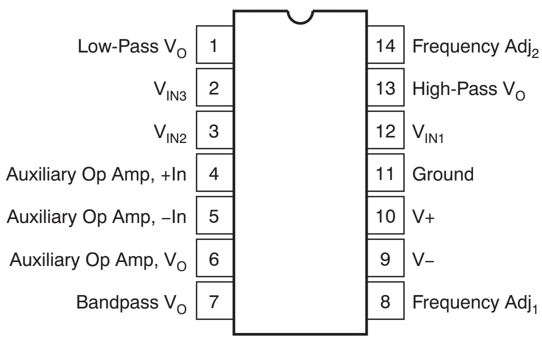
ORDERING INFORMATION(1)

PRODUCT	PACKAGE-LEAD	PACKAGE DESIGNATOR	PACKAGE MARKING
UAF42AP	PDIP-14	N	UAF42AP
UAF42APG4			
UAF42AU	SOIC-16	DW	UAF42AU
UAF42AUE4			

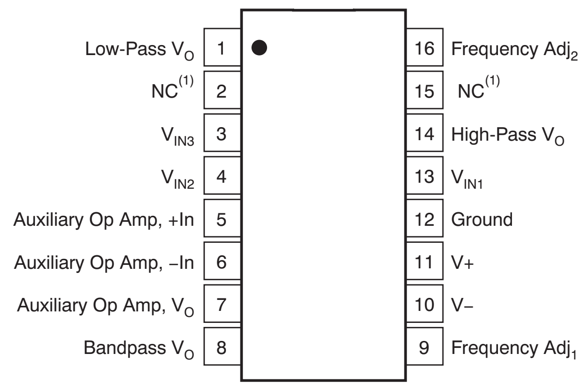
(1) For the most current package and ordering information see the Package Option Addendum at the end of this document, or see the TI web site at www.ti.com.

PIN CONFIGURATIONS

P PACKAGE
PDIP-14
(TOP VIEW)



U PACKAGE
SOIC-16
(TOP VIEW)



NOTE: (1) NC = no connection. For best performance connect all *NC* pins to ground to minimize inter-lead capacitance.

ELECTRICAL CHARACTERISTICS

At T_A = +25°C, and V_S = ±15V, unless otherwise noted.

PARAMETER	CONDITIONS	UAF42AP, AU			UNIT
		MIN	TYP	MAX	
FILTER PERFORMANCE					
Frequency Range, f_n			0 to 100		kHz
Frequency Accuracy	f = 1kHz			1	%
vs Temperature			0.01		%/°C
Maximum Q			400		—
Maximum (Q • Frequency) Product			500		kHz
Q vs Temperature	$(f_O \bullet Q) < 10^4$		0.01		%/°C
	$(f_O \bullet Q) < 10^5$		0.025		%/°C
Q Repeatability	$(f_O \bullet Q) < 10^5$		2		%
Offset Voltage, Low-Pass Output				±5	mV
Resistor Accuracy			0.5	1	%
OFFSET VOLTAGE(1)					
Input Offset Voltage			±0.5	±5	mV
vs Temperature			±3		μV/°C
vs Power Supply	V_S = ±6V to ±18V	80	96		dB
INPUT BIAS CURRENT(1)					
Input Bias Current	V_{CM} = 0V		10	50	pA
Input Offset Current	V_{CM} = 0V		5		pA
NOISE					
Input Voltage Noise					
Noise Density: f = 10Hz			25		nV/√Hz
Noise Density: f = 10kHz			10		nV/√Hz
Voltage Noise: BW = 0.1Hz to 10Hz			2		μV_{PP}
Input Bias Current Noise					
Noise Density: f = 10kHz			2		fA/√Hz
INPUT VOLTAGE RANGE(1)					
Common-Mode Input Range			±11.5		V
Common-Mode Rejection	V_{CM} = ±10V	80	96		dB
INPUT IMPEDANCE(1)					
Differential			10^{13} || 2		Ω || pF
Common-Mode			10^{13} || 6		Ω || pF
OPEN-LOOP GAIN(1)					
Open-Loop Voltage Gain	V_O = ±10V, R_L= 2kΩ	90	126		dB
FREQUENCY RESPONSE					
Slew Rate			10		V/μs
Gain-Bandwidth Product	G = +1		4		MHz
Total Harmonic Distortion	G = +1, f = 1kHz		0.1		%
OUTPUT(1)					
Voltage Output	R_L = 2kΩ	±11	±11.5		V
Short Circuit Current			±25		mA

(1) Specifications apply to uncommitted op amp, A_4. The three op amps forming the filter are identical to A_4 but are tested as a complete filter.

ELECTRICAL CHARACTERISTICS (continued)

At T_A = +25°C, and V_S = ±15V, unless otherwise noted.

PARAMETER	CONDITIONS	UAF42AP, AU			UNIT
		MIN	TYP	MAX	
POWER SUPPLY					
Specified Operating Voltage			±15		V
Operating Voltage Range		±6		±18	V
Current			±6	±7	mA
TEMPERATURE RANGE					
Specified		–25		+85	°C
Operating		–25		+85	°C
Storage		–40		+125	°C
Thermal Resistance, θ_{JA}			100		°C/W

APPLICATION INFORMATION

The UAF42 is a monolithic implementation of the proven state-variable analog filter topology. This device is pin-compatible with the popular UAF41 analog filter, and it provides several improvements.

The slew rate of the UAF42 has been increased to 10V/μs, versus 1.6V/μs for the UAF41. Frequency • Q product of the UAF42 has been improved, and the useful natural frequency extended by a factor of four to 100kHz. FET input op amps on the UAF42 provide very low input bias current. The monolithic construction of the UAF42 provides lower cost and improved reliability.

DESIGN PROGRAM

Application report SBFA002 (available for download at www.ti.com) and a computer-aided design program also available from Texas Instruments, make it easy to design and implement many kinds of active filters. The DOS-compatible program guides you through the design process and automatically calculates component values.

Low-pass, high-pass, band-pass and band-reject (notch) filters can be designed. The program supports the three most commonly-used all-pole filter types: Butterworth, Chebyshev and Bessel. The less-familiar inverse Chebyshev is also supported, providing a smooth passband response with ripple in the stop band.

With each data entry, the program automatically calculates and displays filter performance. This feature allows a spreadsheet-like *what-if* design approach. For example, a user can quickly determine, by trial and error, how many poles are required for a desired attenuation in the stopband. Gain/phase plots may be viewed for any response type.

The basic building element of the most commonly-used filter types is the second-order section. This section provides a complex-conjugate pair of poles. The natural frequency, ω_n, and Q of the pole pair determine the characteristic response of the section. The low-pass transfer function is shown in Equation 1:

$$\frac{V_O(s)}{V_I(s)} = \frac{A_{LP}\omega_n^2}{s^2 + s\,\omega_n/Q + \omega_n^2} \quad (1)$$

The high-pass transfer function is given by Equation 2:

$$\frac{V_{HP}(s)}{V_I(s)} = \frac{A_{HP}s^2}{s^2 + s\,\omega_n/Q + \omega_n^2} \quad (2)$$

The band-pass transfer function is calculated using Equation 3:

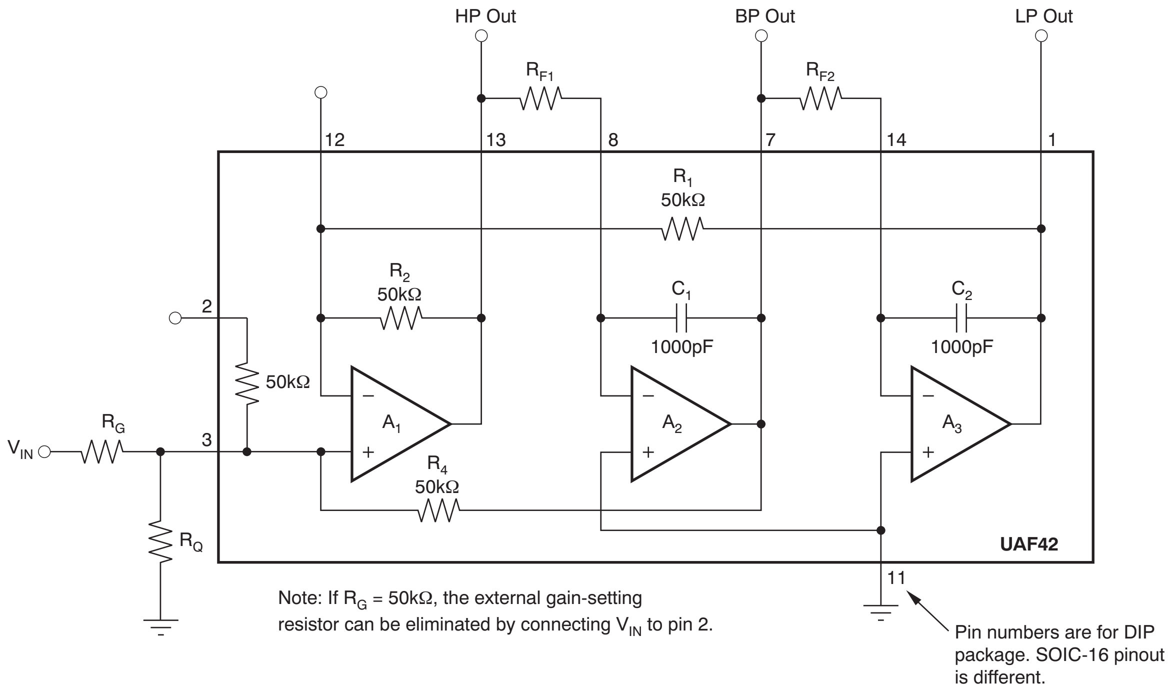
$$\frac{V_{BP}(s)}{V_I(s)} = \frac{A_{BP}(\omega_n/Q)\,s}{s^2 + s\,\omega_n/Q + \omega_n^2} \quad (3)$$

A band-reject response is obtained by summing the low-pass and high-pass outputs, yielding the transfer function shown in Equation 4:

$$\frac{V_{BR}(s)}{V_I(s)} = \frac{A_{BR}(s^2 + \omega_n^2)}{s^2 + s\,\omega_n/Q + \omega_n^2} \quad (4)$$

The most common filter types are formed with one or more cascaded second-order sections. Each section is designed for ω_n and Q according to the filter type (Butterworth, Bessel, Chebyshev, etc.) and cutoff frequency. While tabulated data can be found in virtually any filter design text, the design program eliminates this tedious procedure.

Second-order sections may be noninverting (Figure 1) or inverting (Figure 2). Design equations for these two basic configurations are shown for reference. The design program solves these equations, providing complete results, including component values.



Design Equations

1. $$\omega_n^2 = \frac{R_2}{R_1 R_{F1} R_{F2} C_1 C_2}$$

2. $$Q = \frac{1 + \frac{R_4 (R_G + R_Q)}{R_G R_Q}}{1 + \frac{R_2}{R_1}} \left(\frac{R_2 R_{F1} C_1}{R_1 R_{F2} C_2} \right)^{1/2}$$

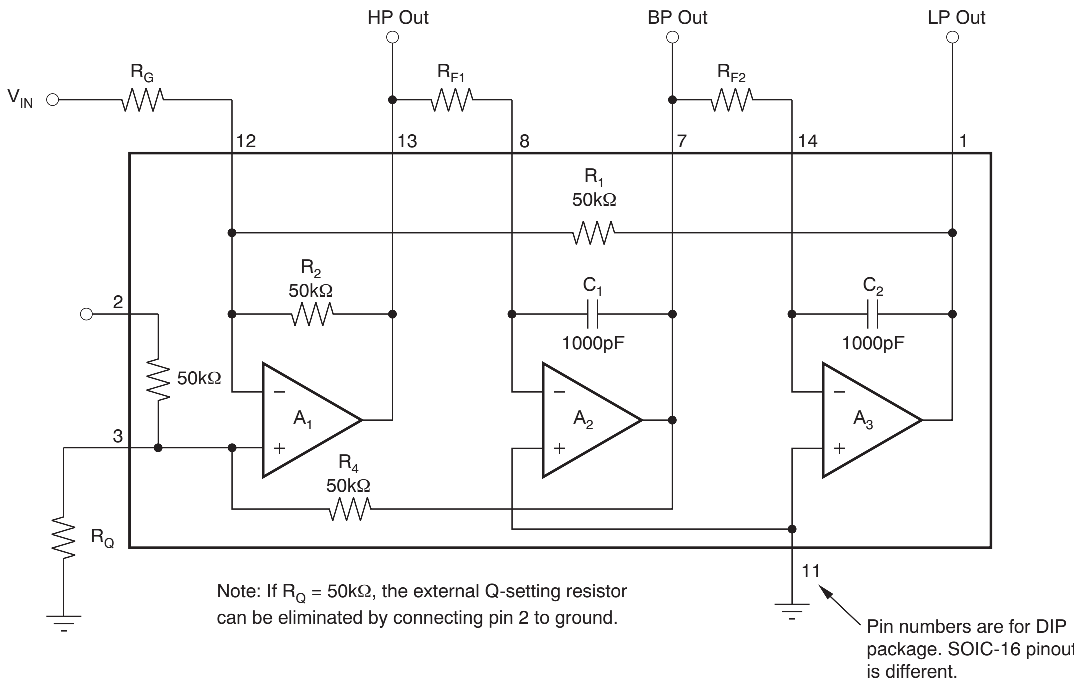
3. $$QA_{LP} = QA_{HP} \left(\frac{R_1}{R_2} \right) = A_{BP} \left(\frac{R_1 R_{F1} C_1}{R_2 R_{F2} C_2} \right)^{1/2}$$

4. $$A_{LP} = \frac{1 + \frac{R_1}{R_2}}{R_G \left(\frac{1}{R_G} + \frac{1}{R_Q} + \frac{1}{R_4} \right)}$$

5. $$A_{HP} = \frac{R_2}{R_1} A_{LP} = \frac{1 + \frac{R_2}{R_1}}{R_G \left(\frac{1}{R_G} + \frac{1}{R_Q} + \frac{1}{R_4} \right)}$$

6. $$A_{BP} = \frac{R_4}{R_G}$$

Figure 1. Noninverting Pole-Pair



Design Equations

1. $$\omega_n^2 = \frac{R_2}{R_1 R_{F1} R_{F2} C_1 C_2}$$

2. $$Q = \left(1 + \frac{R_4}{R_Q}\right) \frac{1}{\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_G}\right)} \left(\frac{R_{F1} C_1}{R_1 R_2 R_{F2} C_2}\right)^{1/2}$$

3. $$QA_{LP} = QA_{HP} \left(\frac{R_1}{R_2}\right) = A_{BP} \left(\frac{R_1 R_{F1} C_1}{R_2 R_{F2} C_2}\right)^{1/2}$$

4. $$A_{LP} = \frac{R_1}{R_G}$$

5. $$A_{HP} = \frac{R_2}{R_1} A_{LP} = \frac{R_2}{R_G}$$

6. $$A_{BP} = \left(1 + \frac{R_4}{R_Q}\right) \frac{1}{R_G \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_G}\right)}$$

Figure 2. Inverting Pole-Pair

REVISION HISTORY

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision A (November, 2007) to Revision B	Page
• Corrected package marking information shown in *Ordering Information* table	2

PACKAGING INFORMATION

Orderable Device	Status (1)	Package Type	Package Drawing	Pins	Package Qty	Eco Plan (2)	Lead/Ball Finish (6)	MSL Peak Temp (3)	Op Temp (°C)	Device Marking (4/5)	Samples
UAF42AP	ACTIVE	PDIP	N	14	25	Green (RoHS & no Sb/Br)	CU NIPDAU	N / A for Pkg Type		UAF42AP	Samples
UAF42APG4	ACTIVE	PDIP	N	14	25	Green (RoHS & no Sb/Br)	CU NIPDAU	N / A for Pkg Type		UAF42AP	Samples
UAF42AU	ACTIVE	SOIC	DW	16	40	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-3-260C-168 HR	-25 to 85	UAF42AU	Samples
UAF42AUE4	ACTIVE	SOIC	DW	16	40	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-3-260C-168 HR	-25 to 85	UAF42AU	Samples

(1) The marketing status values are defined as follows:
ACTIVE: Product device recommended for new designs.
LIFEBUY: TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.
NRND: Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.
PREVIEW: Device has been announced but is not in production. Samples may or may not be available.
OBSOLETE: TI has discontinued the production of the device.

(2) Eco Plan - The planned eco-friendly classification: Pb-Free (RoHS), Pb-Free (RoHS Exempt), or Green (RoHS & no Sb/Br) - please check http://www.ti.com/productcontent for the latest availability information and additional product content details.
TBD: The Pb-Free/Green conversion plan has not been defined.
Pb-Free (RoHS): TI's terms "Lead-Free" or "Pb-Free" mean semiconductor products that are compatible with the current RoHS requirements for all 6 substances, including the requirement that lead not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, TI Pb-Free products are suitable for use in specified lead-free processes.
Pb-Free (RoHS Exempt): This component has a RoHS exemption for either 1) lead-based flip-chip solder bumps used between the die and package, or 2) lead-based die adhesive used between the die and leadframe. The component is otherwise considered Pb-Free (RoHS compatible) as defined above.
Green (RoHS & no Sb/Br): TI defines "Green" to mean Pb-Free (RoHS compatible), and free of Bromine (Br) and Antimony (Sb) based flame retardants (Br or Sb do not exceed 0.1% by weight in homogeneous material)

(3) MSL, Peak Temp. - The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

(4) There may be additional marking, which relates to the logo, the lot trace code information, or the environmental category on the device.

(5) Multiple Device Markings will be inside parentheses. Only one Device Marking contained in parentheses and separated by a "~" will appear on a device. If a line is indented then it is a continuation of the previous line and the two combined represent the entire Device Marking for that device.

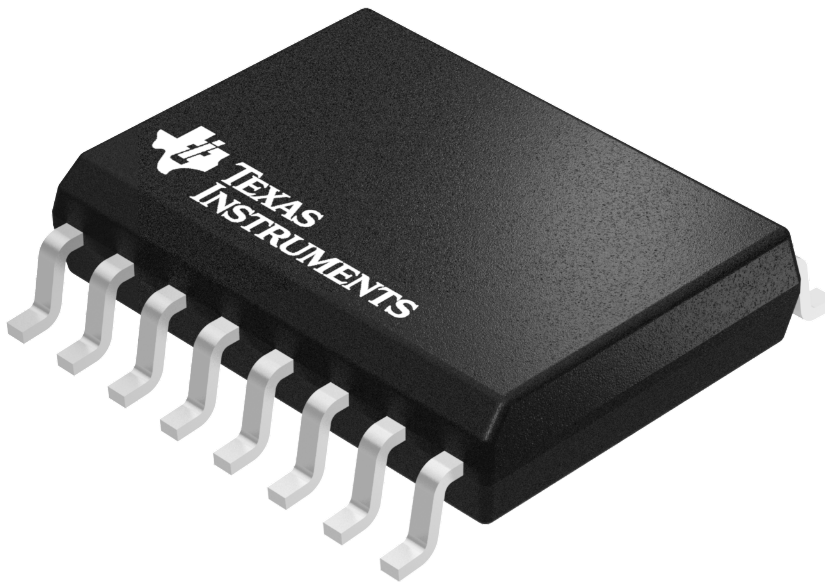
(6) Lead/Ball Finish - Orderable Devices may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead/Ball Finish values may wrap to two lines if the finish value exceeds the maximum column width.

Important Information and Disclaimer: The information provided on this page represents TI's knowledge and belief as of the date that it is provided. TI bases its knowledge and belief on information provided by third parties, and makes no representation or warranty as to the accuracy of such information. Efforts are underway to better integrate information from third parties. TI has taken and continues to take reasonable steps to provide representative and accurate information but may not have conducted destructive testing or chemical analysis on incoming materials and chemicals. TI and TI suppliers consider certain information to be proprietary, and thus CAS numbers and other limited information may not be available for release.

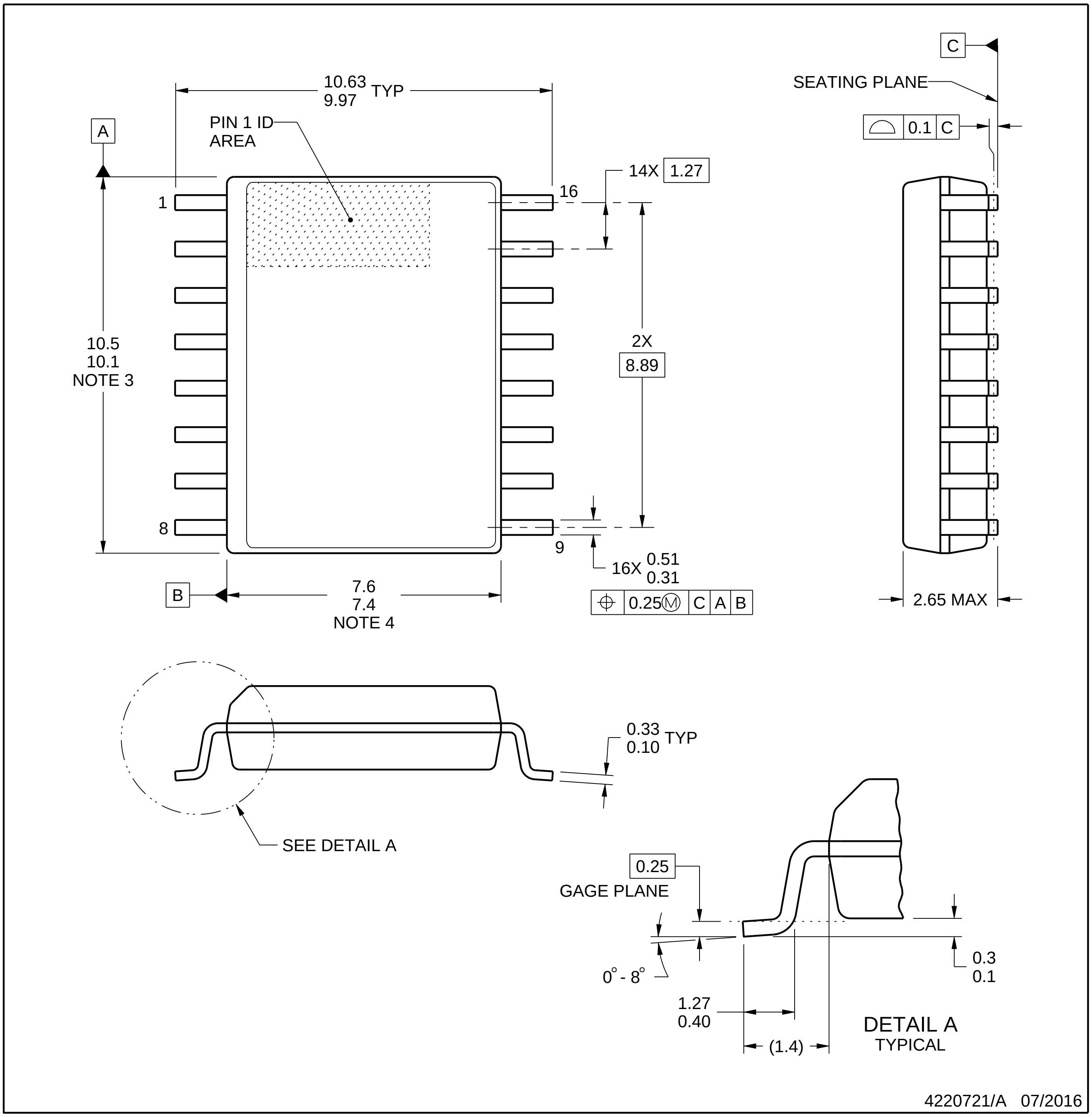
In no event shall TI's liability arising out of such information exceed the total purchase price of the TI part(s) at issue in this document sold by TI to Customer on an annual basis.

DW 16 SOIC - 2.65 mm max height

SMALL OUTLINE INTEGRATED CIRCUIT

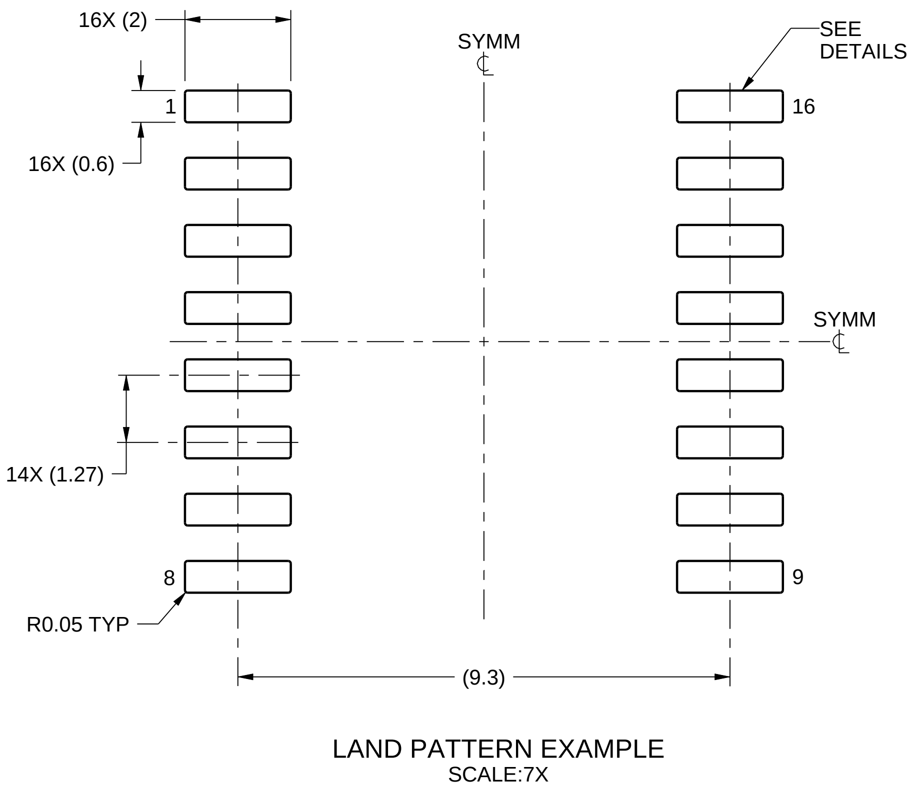


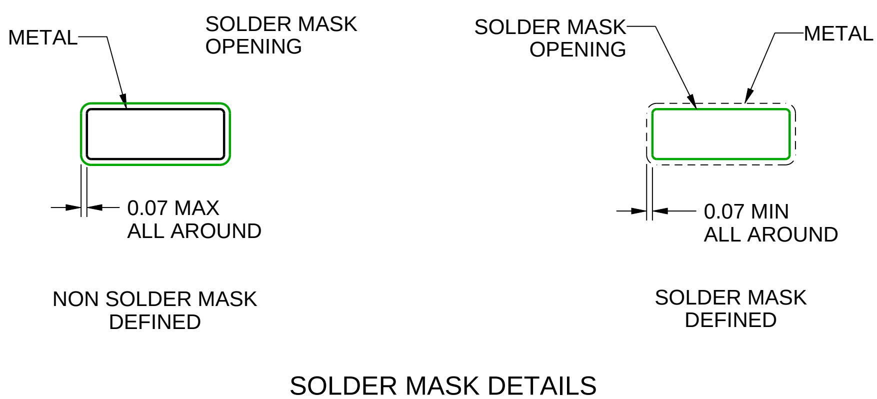
Images above are just a representation of the package family, actual package may vary.
Refer to the product data sheet for package details.



NOTES:

1. All linear dimensions are in millimeters. Dimensions in parenthesis are for reference only. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.
3. This dimension does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.15 mm, per side.
4. This dimension does not include interlead flash. Interlead flash shall not exceed 0.25 mm, per side.
5. Reference JEDEC registration MS-013.

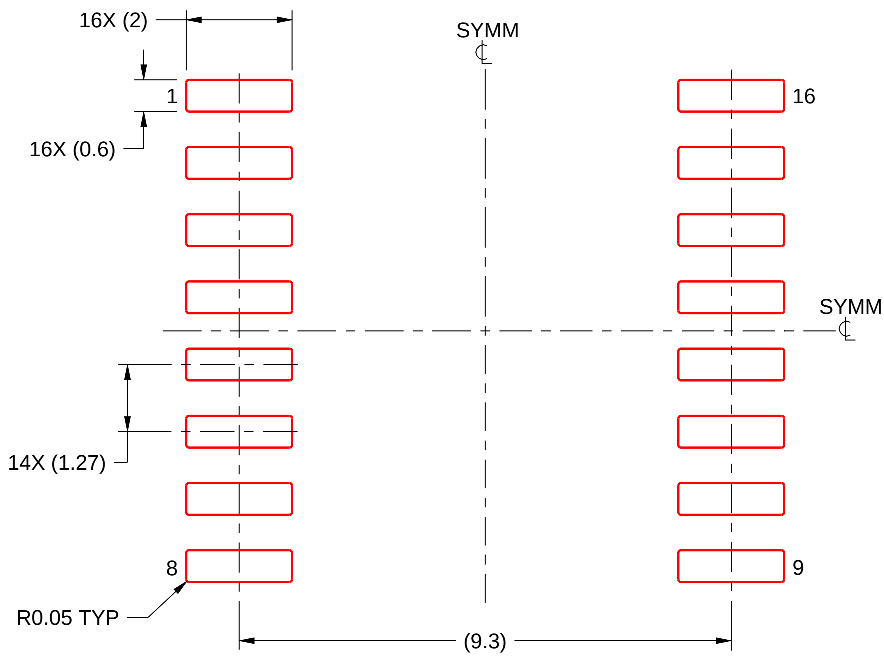




4220721/A 07/2016

NOTES: (continued)

6. Publication IPC-7351 may have alternate designs.
7. Solder mask tolerances between and around signal pads can vary based on board fabrication site.



SOLDER PASTE EXAMPLE
BASED ON 0.125 mm THICK STENCIL
SCALE:7X

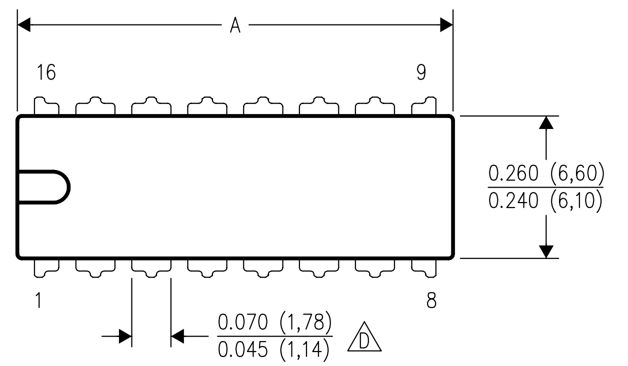
4220721/A 07/2016

NOTES: (continued)

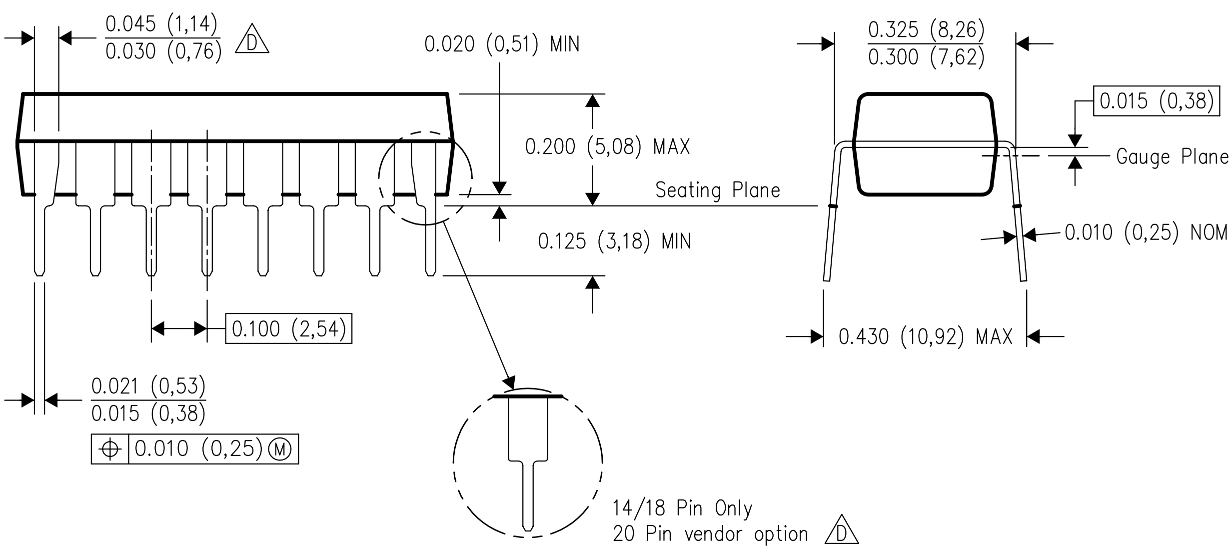
8. Laser cutting apertures with trapezoidal walls and rounded corners may offer better paste release. IPC-7525 may have alternate design recommendations.
9. Board assembly site may have different recommendations for stencil design.

N (R–PDIP–T**) PLASTIC DUAL–IN–LINE PACKAGE

16 PINS SHOWN



PINS ** / DIM	14	16	18	20
A MAX	0.775 (19,69)	0.775 (19,69)	0.920 (23,37)	1.060 (26,92)
A MIN	0.745 (18,92)	0.745 (18,92)	0.850 (21,59)	0.940 (23,88)
C MS–001 VARIATION	AA	BB	AC	AD



4040049/E 12/2002

NOTES:
A. All linear dimensions are in inches (millimeters).
B. This drawing is subject to change without notice.
C. Falls within JEDEC MS–001, except 18 and 20 pin minimum body length (Dim A).
D. The 20 pin end lead shoulder width is a vendor option, either half or full width.

IMPORTANT NOTICE

Texas Instruments Incorporated (TI) reserves the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete.

TI's published terms of sale for semiconductor products (http://www.ti.com/sc/docs/stdterms.htm) apply to the sale of packaged integrated circuit products that TI has qualified and released to market. Additional terms may apply to the use or sale of other types of TI products and services.

Reproduction of significant portions of TI information in TI data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such reproduced documentation. Information of third parties may be subject to additional restrictions. Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyers and others who are developing systems that incorporate TI products (collectively, "Designers") understand and agree that Designers remain responsible for using their independent analysis, evaluation and judgment in designing their applications and that Designers have full and exclusive responsibility to assure the safety of Designers' applications and compliance of their applications (and of all TI products used in or for Designers' applications) with all applicable regulations, laws and other applicable requirements. Designer represents that, with respect to their applications, Designer has all the necessary expertise to create and implement safeguards that (1) anticipate dangerous consequences of failures, (2) monitor failures and their consequences, and (3) lessen the likelihood of failures that might cause harm and take appropriate actions. Designer agrees that prior to using or distributing any applications that include TI products, Designer will thoroughly test such applications and the functionality of such TI products as used in such applications.

TI's provision of technical, application or other design advice, quality characterization, reliability data or other services or information, including, but not limited to, reference designs and materials relating to evaluation modules, (collectively, "TI Resources") are intended to assist designers who are developing applications that incorporate TI products; by downloading, accessing or using TI Resources in any way, Designer (individually or, if Designer is acting on behalf of a company, Designer's company) agrees to use any particular TI Resource solely for this purpose and subject to the terms of this Notice.

TI's provision of TI Resources does not expand or otherwise alter TI's applicable published warranties or warranty disclaimers for TI products, and no additional obligations or liabilities arise from TI providing such TI Resources. TI reserves the right to make corrections, enhancements, improvements and other changes to its TI Resources. TI has not conducted any testing other than that specifically described in the published documentation for a particular TI Resource.

Designer is authorized to use, copy and modify any individual TI Resource only in connection with the development of applications that include the TI product(s) identified in such TI Resource. NO OTHER LICENSE, EXPRESS OR IMPLIED, BY ESTOPPEL OR OTHERWISE TO ANY OTHER TI INTELLECTUAL PROPERTY RIGHT, AND NO LICENSE TO ANY TECHNOLOGY OR INTELLECTUAL PROPERTY RIGHT OF TI OR ANY THIRD PARTY IS GRANTED HEREIN, including but not limited to any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information regarding or referencing third-party products or services does not constitute a license to use such products or services, or a warranty or endorsement thereof. Use of TI Resources may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

TI RESOURCES ARE PROVIDED "AS IS" AND WITH ALL FAULTS. TI DISCLAIMS ALL OTHER WARRANTIES OR REPRESENTATIONS, EXPRESS OR IMPLIED, REGARDING RESOURCES OR USE THEREOF, INCLUDING BUT NOT LIMITED TO ACCURACY OR COMPLETENESS, TITLE, ANY EPIDEMIC FAILURE WARRANTY AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, AND NON-INFRINGEMENT OF ANY THIRD PARTY INTELLECTUAL PROPERTY RIGHTS. TI SHALL NOT BE LIABLE FOR AND SHALL NOT DEFEND OR INDEMNIFY DESIGNER AGAINST ANY CLAIM, INCLUDING BUT NOT LIMITED TO ANY INFRINGEMENT CLAIM THAT RELATES TO OR IS BASED ON ANY COMBINATION OF PRODUCTS EVEN IF DESCRIBED IN TI RESOURCES OR OTHERWISE. IN NO EVENT SHALL TI BE LIABLE FOR ANY ACTUAL, DIRECT, SPECIAL, COLLATERAL, INDIRECT, PUNITIVE, INCIDENTAL, CONSEQUENTIAL OR EXEMPLARY DAMAGES IN CONNECTION WITH OR ARISING OUT OF TI RESOURCES OR USE THEREOF, AND REGARDLESS OF WHETHER TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

Unless TI has explicitly designated an individual product as meeting the requirements of a particular industry standard (e.g., ISO/TS 16949 and ISO 26262), TI is not responsible for any failure to meet such industry standard requirements.

Where TI specifically promotes products as facilitating functional safety or as compliant with industry functional safety standards, such products are intended to help enable customers to design and create their own applications that meet applicable functional safety standards and requirements. Using products in an application does not by itself establish any safety features in the application. Designers must ensure compliance with safety-related requirements and standards applicable to their applications. Designer may not use any TI products in life-critical medical equipment unless authorized officers of the parties have executed a special contract specifically governing such use. Life-critical medical equipment is medical equipment where failure of such equipment would cause serious bodily injury or death (e.g., life support, pacemakers, defibrillators, heart pumps, neurostimulators, and implantables). Such equipment includes, without limitation, all medical devices identified by the U.S. Food and Drug Administration as Class III devices and equivalent classifications outside the U.S.

TI may expressly designate certain products as completing a particular qualification (e.g., Q100, Military Grade, or Enhanced Product). Designers agree that it has the necessary expertise to select the product with the appropriate qualification designation for their applications and that proper product selection is at Designers' own risk. Designers are solely responsible for compliance with all legal and regulatory requirements in connection with such selection.

Designer will fully indemnify TI and its representatives against any damages, costs, losses, and/or liabilities arising out of Designer's non-compliance with the terms and provisions of this Notice.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265

BURR - BROWN® APPLICATION BULLETIN
Mailing Address: PO Box 11400 • Tucson, AZ 85734 • Street Address: 6730 S. Tucson Blvd. • Tucson, AZ 85706
Tel: (602) 746-1111 • Twx: 910-952-111 • Telex: 066-6491 • FAX (602) 889-1510 • Immediate Product Info: (800) 548-6132

FILTER DESIGN PROGRAM FOR THE UAF42 UNIVERSAL ACTIVE FILTER

By Johnnie Molina and R. Mark Stitt (602) 746-7592

Although active filters are vital in modern electronics, their design and verification can be tedious and time consuming. To aid in the design of active filters, Burr-Brown provides a series of FilterPro™ computer-aided design programs. Using the FILTER42 program and the UAF42 it is easy to design and implement all kinds of active filters. The UAF42 is a monolithic IC which contains the op amps, matched resistors, and precision capacitors needed for a state-variable filter pole-pair. A fourth, uncommitted precision op amp is also included on the die.

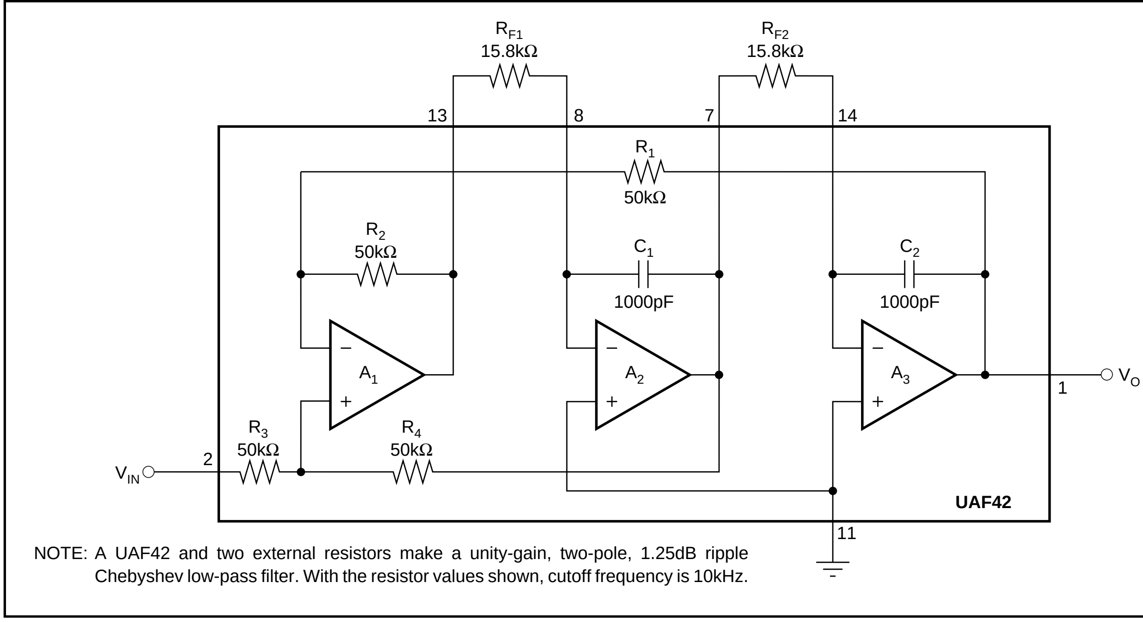
Filters implemented with the UAF42 are time-continuous, free from the switching noise and aliasing problems of switched-capacitor filters. Other advantages of the state-variable topology include low sensitivity of filter parameters to external component values and simultaneous low-pass, high-pass, and band-pass outputs. Simple two-pole filters can be made with a UAF42 and two external resistors—see Figure 1.

The DOS-compatible program guides you through the design process and automatically calculates component values. Low-pass, high-pass, band-pass, and band-reject (or notch) filters can be designed.

Active filters are designed to approximate an ideal filter response. For example, an ideal low-pass filter completely eliminates signals above the cutoff frequency (in the stop-band), and perfectly passes signals below it (in the pass-band). In real filters, various trade-offs are made in an attempt to approximate the ideal. Some filter types are optimized for gain flatness in the pass-band, some trade-off gain variation or ripple in the pass-band for a steeper rate of attenuation between the pass-band and stop-band (in the transition-band), still others trade-off both flatness and rate of roll-off in favor of pulse-response fidelity. FILTER42 supports the three most commonly used all-pole filter types: Butterworth, Chebyshev, and Bessel. The less familiar Inverse Chebyshev is also supported. If a two-pole band-pass or notch filter is selected, the program defaults to a resonant-circuit response.

Butterworth (maximally flat magnitude). This filter has the flattest possible pass-band magnitude response. Attenuation is –3dB at the design cutoff frequency. Attenuation beyond the cutoff frequency is a moderately steep –20dB/decade/pole. The pulse response of the Butterworth filter has moderate overshoot and ringing.

Chebyshev (equal ripple magnitude). (Other transliterations of the Russian Heby]ov are Tschebychev, Tschebyscheff or Tchevysheff). This filter response has steeper initial rate of attenuation beyond the cutoff frequency than Butterworth.



NOTE: A UAF42 and two external resistors make a unity-gain, two-pole, 1.25dB ripple Chebyshev low-pass filter. With the resistor values shown, cutoff frequency is 10kHz.

FIGURE 1. Two-Pole Low-Pass Filter Using UAF42.

Printed in U.S.A. July, 1993

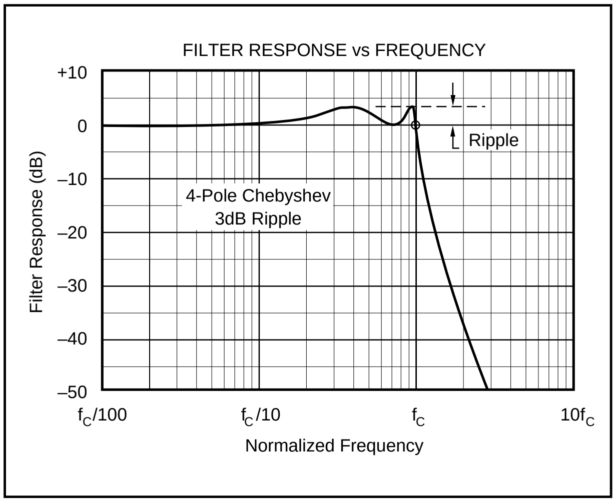


FIGURE 2A. Response vs Frequency for Even-Order (4-pole) 3dB Ripple Chebyshev Low-Pass Filter Showing Cutoff at 0dB.

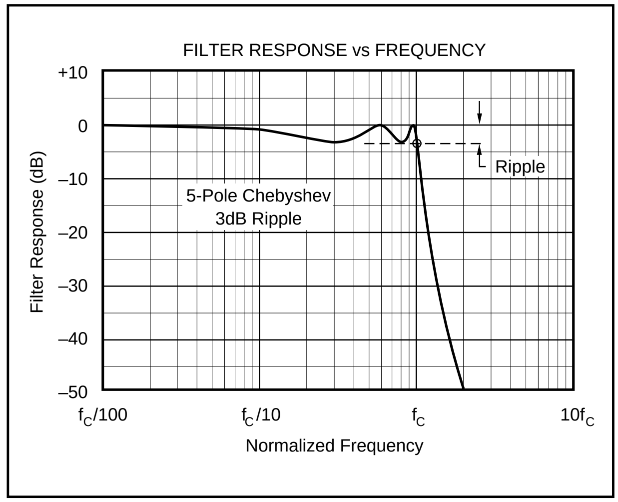


FIGURE 2B. Response vs Frequency for Odd-Order (5-pole) 3dB Ripple Chebyshev Low-Pass Filter Showing Cutoff at –3dB.

This advantage comes at the penalty of amplitude variation (ripple) in the pass-band. Unlike Butterworth and Bessel responses, which have 3dB attenuation at the cutoff frequency, Chebyshev cutoff frequency is defined as the frequency at which the response falls below the ripple band. For even-order filters, all ripple is above the dc-normalized passband gain response, so cutoff is at 0dB (see Figure 2A). For odd-order filters, all ripple is below the dc-normalized passband gain response, so cutoff is at –(ripple) dB (see Figure 2B). For a given number of poles, a steeper cutoff can be achieved by allowing more pass-band ripple. The Chebyshev has more ringing in its pulse response than the Butterworth—especially for high-ripple designs.

Inverse Chebyshev (equal minima of attenuation in the stop band). As its name implies, this filter type is cousin to the Chebyshev. The difference is that the ripple of the Inverse Chebyshev filter is confined to the stop-band. This filter type has a steep rate of roll-off and a flat magnitude response in the pass-band. Cutoff of the Inverse Chebyshev is defined as the frequency where the response first enters the specified stop-band—see Figure 3. Step response of the Inverse Chebyshev is similar to the Butterworth.

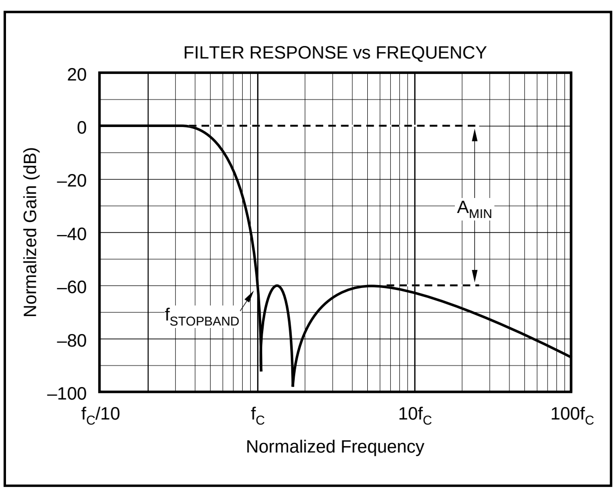


FIGURE 3. Response vs Frequency for 5-pole, –60dB Stop-Band, Inverse Chebyshev Low-Pass Filter Showing Cutoff at –60dB.

Bessel (maximally flat time delay), also called Thomson. Due to its linear phase response, this filter has excellent pulse response (minimal overshoot and ringing). For a given number of poles, its magnitude response is not as flat, nor is its initial rate of attenuation beyond the –3dB cutoff frequency as steep as the Butterworth. It takes a higher-order Bessel filter to give a magnitude response similar to a given Butterworth filter, but the pulse response fidelity of the Bessel filter may make the added complexity worthwhile.

Tuned Circuit (resonant or tuned-circuit response). If a two-pole band-pass or band-reject (notch) filter is selected, the program defaults to a tuned circuit response. When band-pass response is selected, the filter design approximates the response of a series-connected LC circuit as shown in Figure 4A. When a two-pole band-reject (notch) response is selected, filter design approximates the response of a parallel-connected LC circuit as shown in Figure 4B.

CIRCUIT IMPLEMENTATION

In general, filters designed by this program are implemented with cascaded filter subcircuits. Subcircuits either have a two-pole (complex pole-pair) response or a single real-pole response. The program automatically selects the subcircuits required based on function and performance. A program option allows you to override the automatic topology selection routine to specify either an inverting or noninverting pole-pair configuration.

The simplest filter circuit consists of a single pole-pair subcircuit as shown in Figure 5. More complex filters consist of two or more cascaded subcircuits as shown in Figure 6. Even-order filters are implemented entirely with UAF42 pole-pair sections and normally require no external capacitors. Odd-order filters additionally require one real pole section which can be implemented with the fourth uncommitted op amp in the UAF42, an external resistor, and an external capacitor. The program can be used to design filters up to tenth order.

The program guides you through the filter design and generates component values and a block diagram describing the filter circuit. The *Filter Block Diagram* program output shows the subcircuits needed to implement the filter design labeled by type and connected in the recommended order. The *Filter Component Values* program output shows the values of all external components needed to implement the filter.

SUMMARY OF FILTER TYPES

Butterworth

Advantages: Maximally flat magnitude response in the pass-band. Good all-around performance. Pulse response better than Chebyshev. Rate of attenuation better than Bessel.

Disadvantages: Some overshoot and ringing in step response.

Chebyshev

Advantages: Better rate of attenuation beyond the pass-band than Butterworth.

Disadvantages: Ripple in pass-band. Considerably more ringing in step response than Butterworth.

Inverse Chebyshev

Advantages: Flat magnitude response in pass-band with steep rate of attenuation in transition-band.

Disadvantages: Ripple in stop-band. Some overshoot and ringing in step response.

Bessel

Advantages: Best step response—very little overshoot or ringing.

Disadvantages: Slower initial rate of attenuation beyond the pass-band than Butterworth.

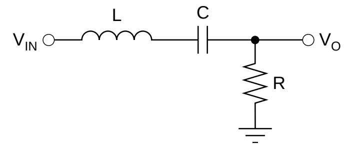


FIGURE 4A. n = 2 Band-Pass Filter Using UAF42 (approximates the response of a series-connected tuned L, C, R circuit).

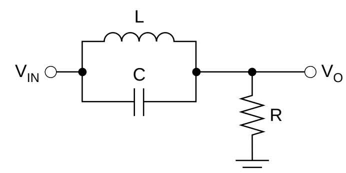
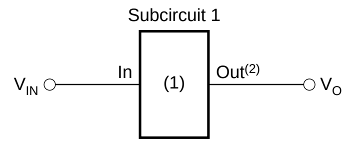
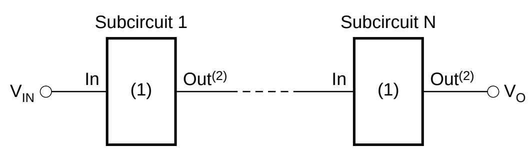


FIGURE 4B. n = 2 Band-Reject (Notch) Filter Using UAF42 (approximates the response of a parallel-connected tuned L, C, R circuit).



NOTES:
(1) Subcircuit will be a complex pole-pair (PP1 through PP6) subcircuit specified on the *UAF42 Filter Component Values* and *Filter Block Diagram* program outputs.
(2) HP Out, BP Out, LP Out, or Aux Out will be specified on the UAF42 *Filter Block Diagram* program output.

FIGURE 5. Simple Filter Made with Single Complex Pole-Pair Subcircuit.



NOTES:
(1) Subcircuit will be a real-pole high-pass (HP), real-pole low-pass (LP), or complex pole-pair (PP1 through PP6) subcircuit specified on the *UAF42 Filter Component Values* and *Filter Block Diagram* program outputs.
(2) If the subcircuit is a pole-pair section, HP Out, BP Out, LP Out, or Aux Out will be specified on the UAF42 *Filter Block Diagram* program output.

FIGURE 6. Multiple-Stage Filter Made with Two or More Subcircuits.

The program automatically places lower Q stages ahead of higher Q stages to prevent op amp output saturation due to gain peaking. Even so, peaking may limit input voltage to less than ±10V (V_S = ±15V). The maximum input voltage for each filter design is shown on the *filter block diagram.* If the UAF42 is to be operated on reduced supplies, the maximum input voltage must be derated commensurately. To use the filter with higher input voltages, you can add an input attenuator.

The program designs the simplest filter that provides the desired AC transfer function with a pass-band gain of 1.0V/V. In some cases the program cannot make a unity-gain filter and the pass-band gain will be less than 1.0V/V. In any case, overall filter gain is shown on the *filter block diagram.* If you want a different gain, you can add an additional stage for gain or attenuation as required.

To build the filter, print-out the block diagram and component values. Consider one subcircuit at a time. Match the subcircuit type referenced on the component print-out to its corresponding circuit diagram—see the Filter Subcircuits section of this bulletin.

The *UAF42 Filter Component Values* print-out has places to display every possible external component needed for any subcircuit. Not all of these components will be required for any specific filter design. When no value is shown for a component, omit the component. For example, the detailed schematic diagrams for complex pole-pair subcircuits show external capacitors in parallel with the 1000pF capacitors in the UAF42. No external capacitors are required for filters above approximately 10Hz.

After the subcircuits have been implemented, connect them in series in the order shown on the *filter block diagram.*

FILTER SUBCIRCUITS

Filter designs consist of cascaded complex pole-pair and real-pole subcircuits. Complex pole pair subcircuits are based on the UAF42 state-variable filter topology. Six variations of this circuit can be used, PP1 through PP6. Real pole sections can be implemented with the auxiliary op amp in the UAF42. High-pass (HP) and low-pass (LP) real-pole sections can be used. The subcircuits are referenced with a two or three letter abbreviation on the *UAF42 Filter Component Values* and *Filter Block Diagram* program outputs. Descriptions of each subcircuit follow:

POLE-PAIR (PP) SUBCIRCUITS

In general, all complex pole-pair subcircuits use the UAF42 in the state-variable configuration. The two filter parameters that must be set for the pole-pair are the filter Q and the natural frequency, f_O. External resistors are used to set these parameters. Two resistors, R_{F1} and R_{F2}, must be used to set the pole-pair f_O. A third external resistor, R_Q, is usually needed to set Q.

At low frequencies, the value required for the frequency-setting resistors can be excessive. Resistor values above about 5MΩ can react with parasitic capacitance causing poor filter performance. When f_O is below 10Hz, external capacitors must be added to keep the value of R_{F1} and R_{F2} below 5MΩ . When f_O is in the range of about 10Hz to 32Hz, An external 5.49kΩ resistor, R_{2A}, is added in parallel with the internal resistor, R_2, to reduce R_{F1} and R_{F2} by $\sqrt{10}$ and eliminate the need for external capacitors. At the other extreme, when f_O is above 10kHz, R_{2A}, is added in parallel with R_2 to improve stability.

External filter gain-set resistors, R_G, are always required when using an inverting pole-pair configuration or when using a noninverting configuration with Q < 0.57.

PP1 (Noninverting pole-pair subcircuit using internal gain-set resistor, R_3)—See Figure 7. In the automatic topology selection mode, this configuration is used for all band-pass filter responses. This configuration allows the combination of unity pass-band gain and high Q (up to 400). Since no external gain-set resistor is required, external parts count is minimized.

PP2 (Noninverting pole-pair subcircuit using an external gain-set resistor, R_G)—See Figure 8. This configuration is used when the pole-pair Q is less than 0.57.

PP3 (Inverting pole-pair subcircuit)—See Figure 9A. In the automatic topology selection mode, this configuration is used for the all-pole low-pass and high-pass filter responses. This configuration requires an external gain-set resistor, R_G. With R_G = 50kΩ, low-pass and high-pass gain are unity.

PP4 (Noninverting pole-pair/zero subcircuit)—See Figure 10. In addition to a complex pole-pair, this configuration produces a jω-axis zero (response null) by summing the low-pass and high-pass outputs using the auxiliary op amp, A_4, in the UAF42. In the automatic topology selection mode, this configuration is used for all band-reject (notch) filter responses and Inverse Chebyshev filter types when Q > 0.57. This subcircuit option keeps external parts count low by using the internal gain-set resistor, R_3.

PP5 (Noninverting pole-pair/zero subcircuit)—See Figure 11. In addition to a complex pole-pair, this configuration produces a jω-axis zero (response null) by summing the low-pass and high-pass outputs using the auxiliary op amp, A_4, in the UAF42. In the automatic topology selection mode, this configuration is used for all band-reject (notch) filter responses and Inverse Chebyshev filter types when Q < 0.57. This subcircuit option requires an external gain-set resistor, R_G.

PP6 (Inverting pole-pair/zero subcircuit)—See Figure 12. In addition to a complex pole-pair, this configuration produces a jω-axis zero (response null) by summing the low-pass and high-pass outputs using the auxiliary op amp, A_4, in the UAF42. This subcircuit is only used when you override the automatic topology selection algorithm and specify the inverting pole-pair topology. Then it is used for all band-reject (notch) filter responses and Inverse Chebyshev filter types.

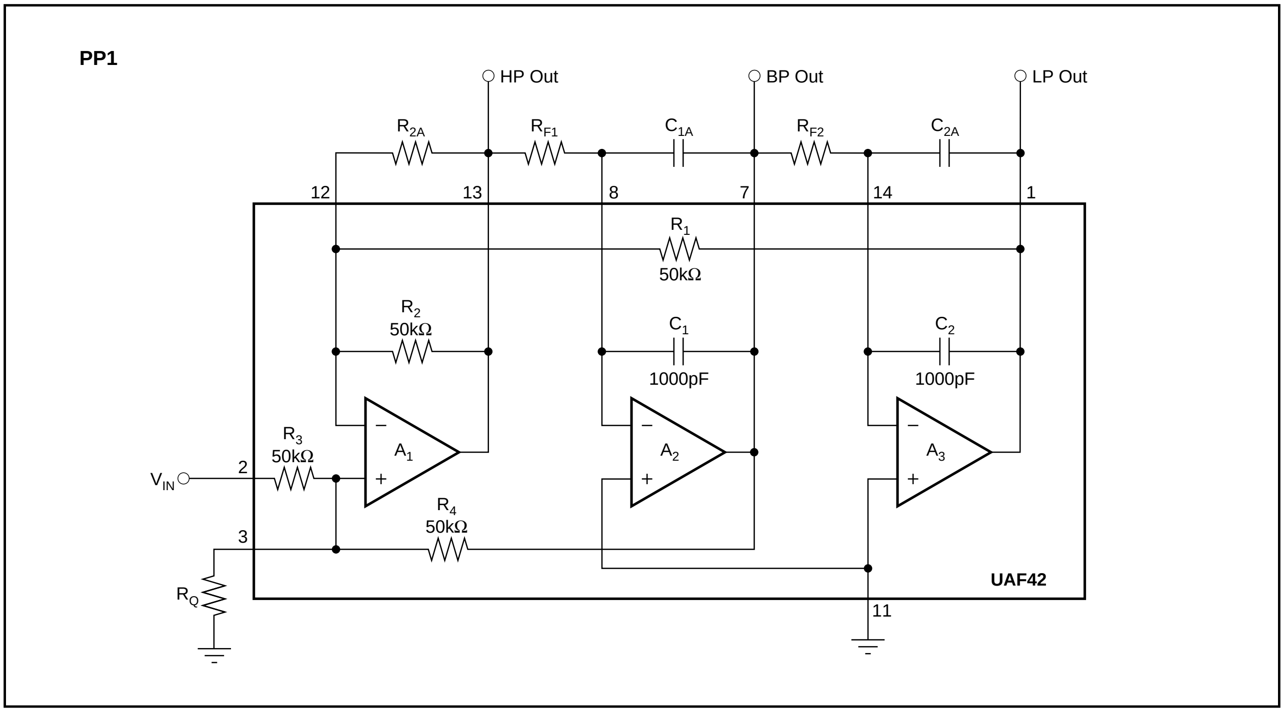


FIGURE 7. PP1 Noninverting Pole-Pair Subcircuit Using Internal Gain-Set Resistor R_3.

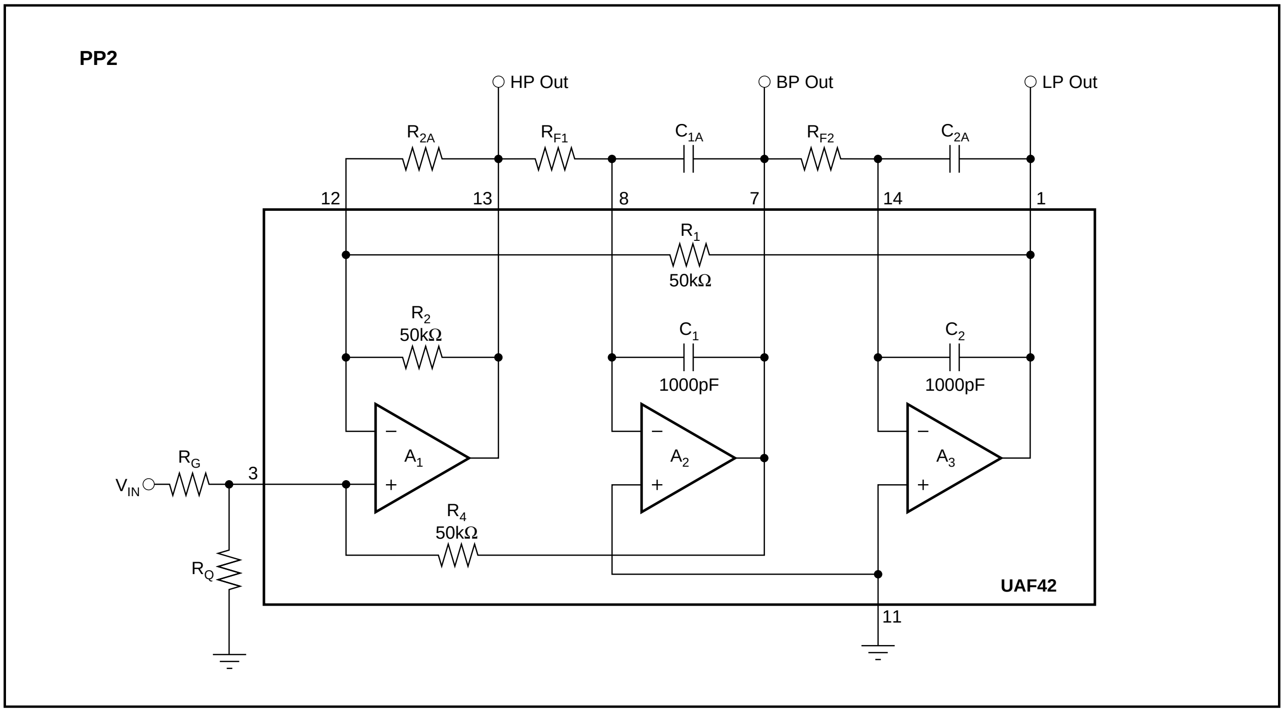


FIGURE 8. PP2 Noninverting Pole-Pair Subcircuit Using External Gain-Set Resistor R_G.

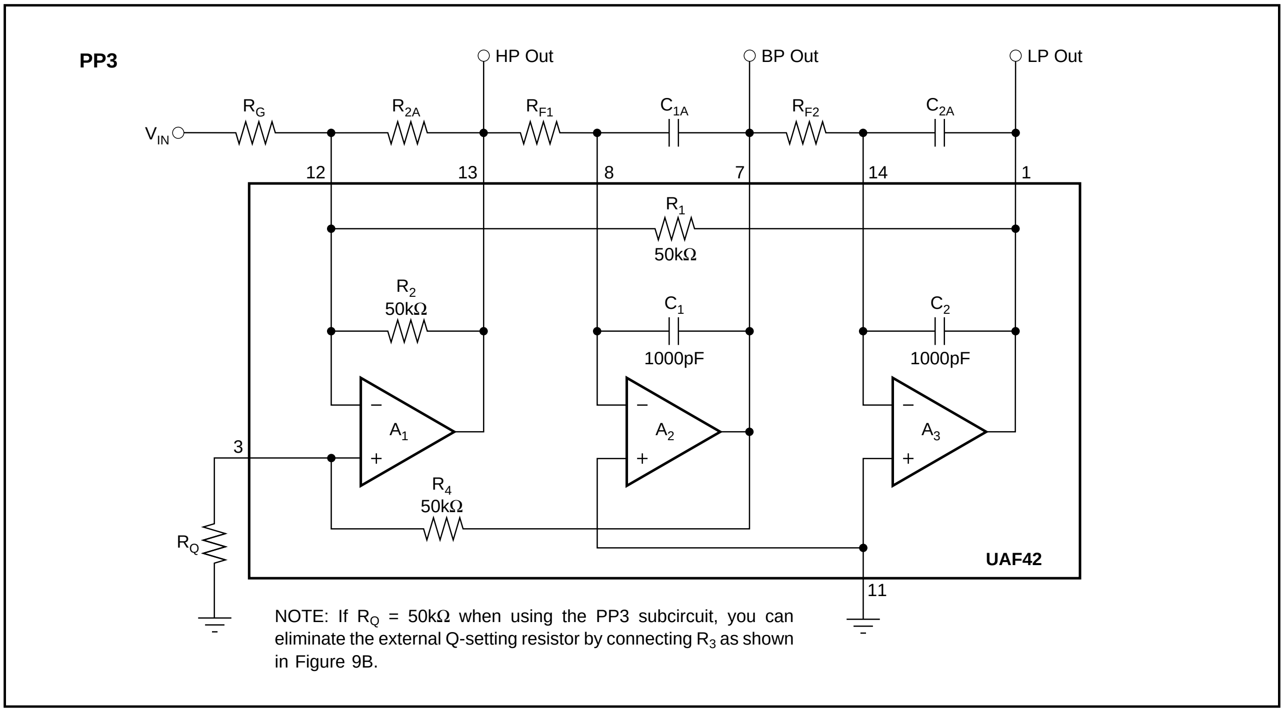


FIGURE 9A. PP3 Inverting Pole-Pair Subcircuit.

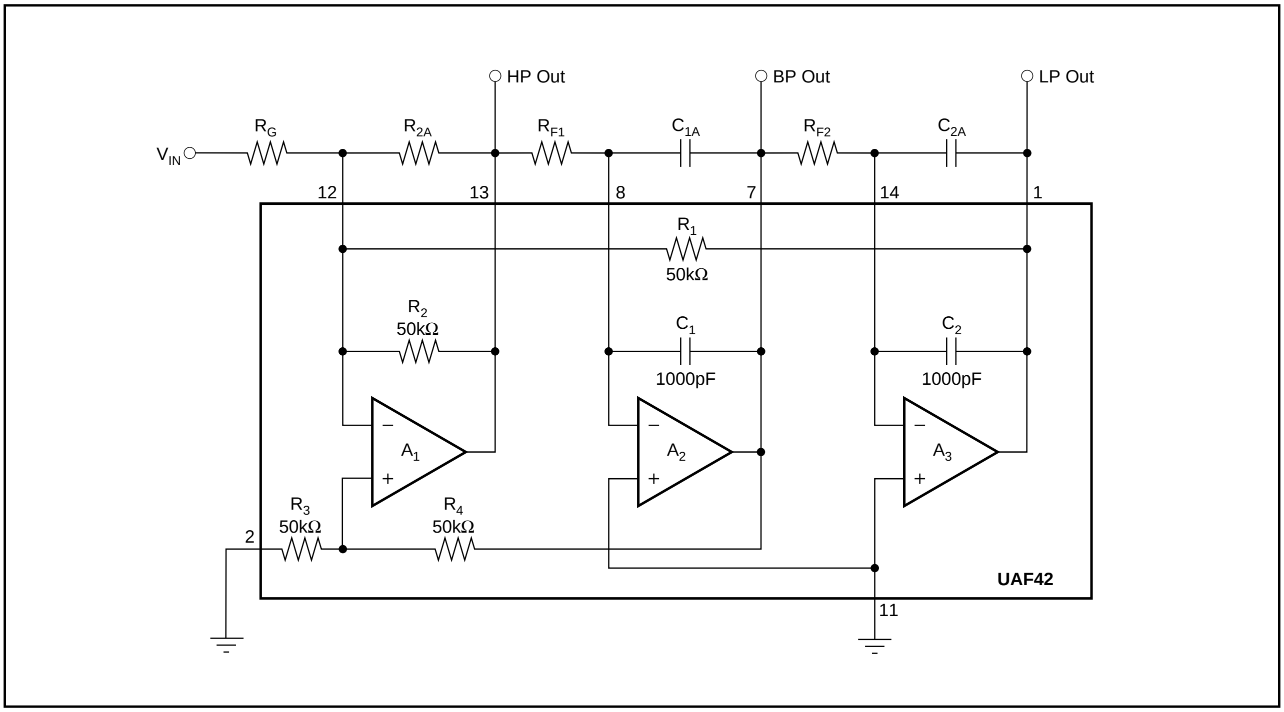


FIGURE 9B. Inverting Pole-Pair Subcircuit Using R_3 to Eliminate External Q-Setting Resistor R_G.

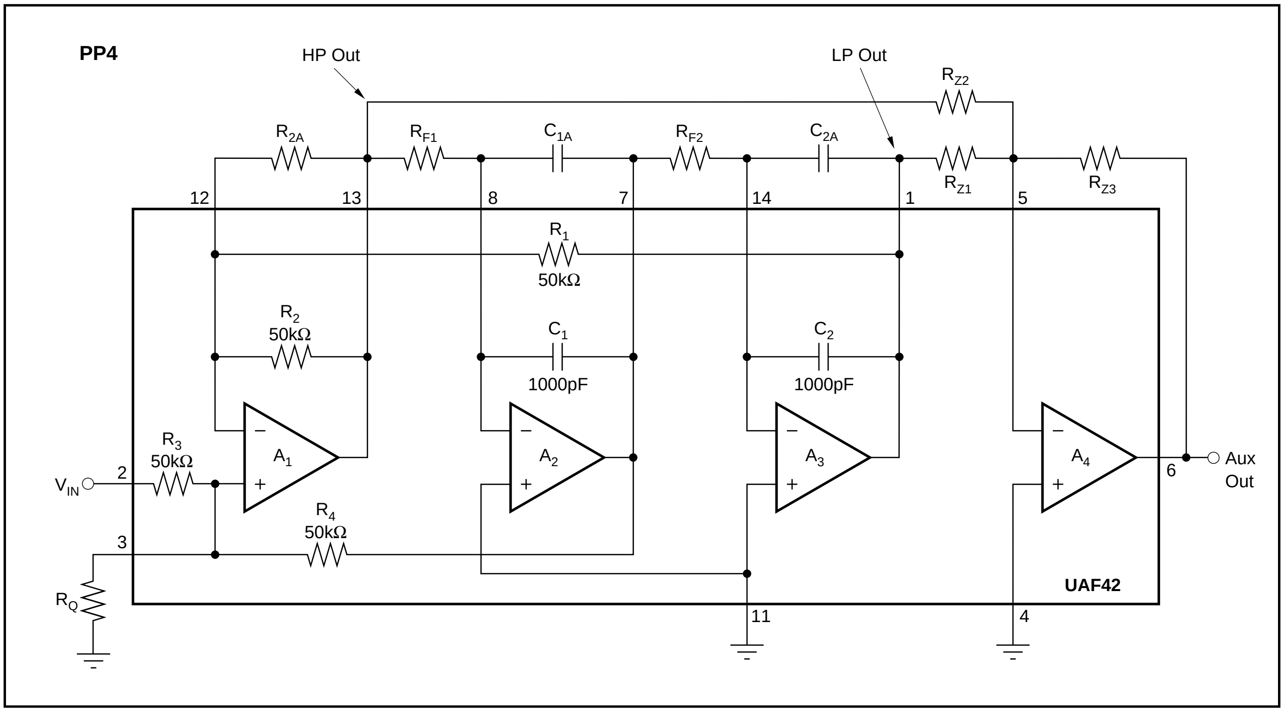


FIGURE 10. PP4 Noninverting Pole-Pair/Zero Subcircuit Using Internal Gain-Set Resistor R_3.

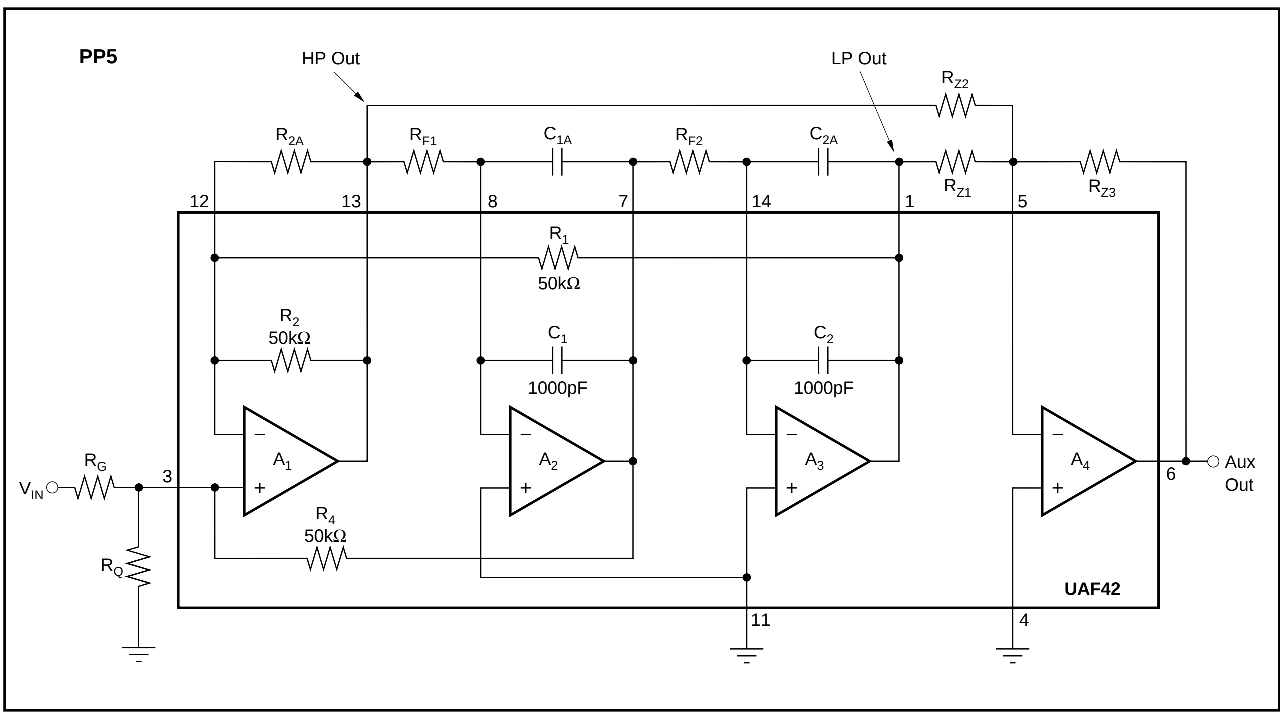


FIGURE 11. PP5 Noninverting Pole-Pair/Zero Subcircuit Using External Gain-Set Resistor R_G.

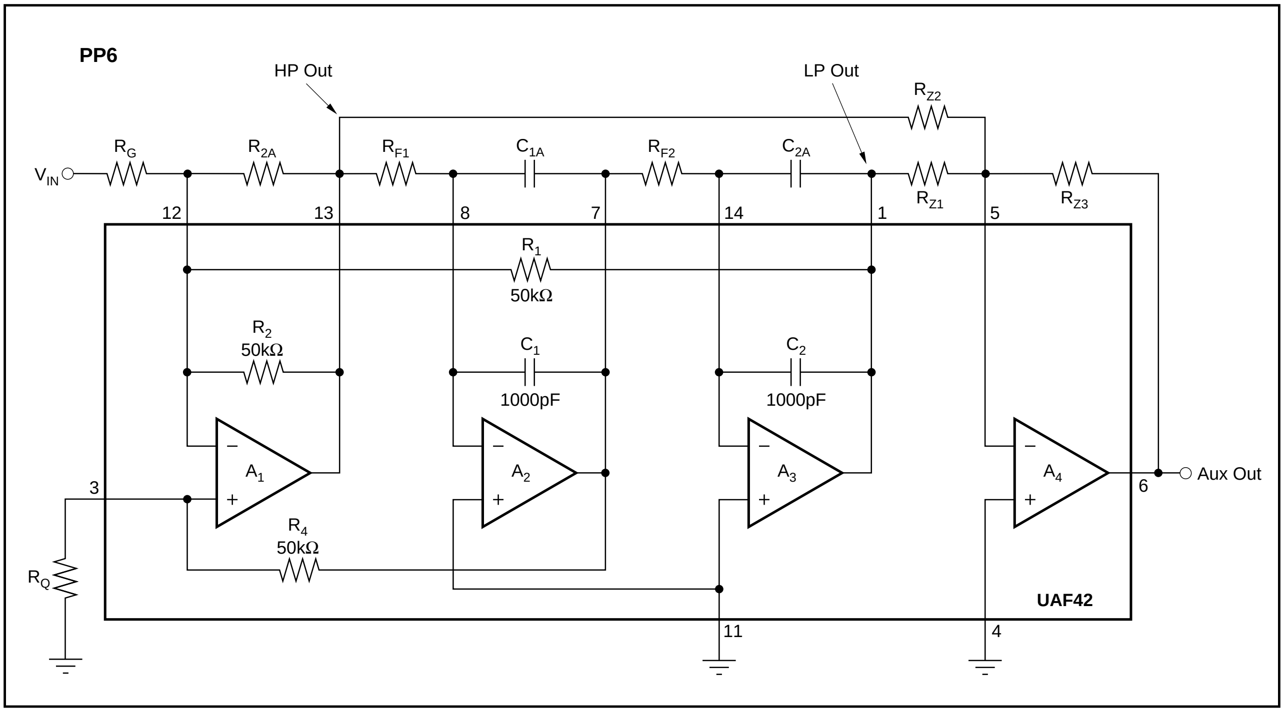


FIGURE 12. PP6 Inverting Pole-Pair/Zero Subcircuit.

This subcircuit option requires an external gain-set resistor, R_G.

LP (Real-pole low-pass subcircuit). The basic low-pass subcircuit (LP) is shown in Figure 13A. A single pole is formed by R_P and C_P. A_2 buffers the output to prevent loading from subsequent stages. If high input impedance is needed, an optional buffer, A_1, can be added to the input.

For an LP subcircuit with gain, use the optional circuit shown in Figure 13B.

For an LP subcircuit with inverting gain or attenuation, use the optional circuit shown in Figure 13C.

HP (Real-pole high-pass subcircuit). The basic high-pass subcircuit (HP) is shown in Figure 14A. A single pole is formed by R_P and C_P. A_2 buffers the output to prevent loading from subsequent stages. If high input impedance is needed, an optional buffer, A_1, can be added to the input.

For an HP subcircuit with gain, use the optional circuit shown in Figure 14B.

For an HP subcircuit with inverting gain or attenuation, use the optional circuit shown in Figure 14C.

IF THE AUXILIARY OP AMP IN A UAF42 IS NOT USED

If the auxiliary op amp in a UAF42 is not used, connect it as a grounded unity-gain follower as shown in Figure 15. This will keep its inputs and output in the linear region of operation to prevent biasing anomalies which may affect the other op amps in the UAF42.

ELIMINATING THE LP SUBCIRCUIT IN ODD-ORDER INVERSE CHEBYSHEV LOW-PASS FILTERS

Odd-order Inverse Chebyshev low-pass filters can be simplified by eliminating the LP input section and forming the real pole in the first pole-pair/zero subcircuit. To form the real pole in the pole-pair/zero subcircuit, place a capacitor, C_1, in parallel with the summing amplifier feedback resistor, R_{Z3}. The real pole must be at the same frequency as in the LP subcircuit. One way to achieve this is to set $C_1 = C_P$ and $R_{Z3} = R_P$, where C_P and R_P are the values that were specified for the LP section. Then, to keep the summing amplifier gains the same, multiply R_{Z1} and R_{Z2} by R_P/R_{Z3}.

Figures 16A and 16B show an example of the modification of a 3-pole circuit. It is a 347Hz-cutoff inverse Chebyshev low-pass filter. This example is from an application which required a low-pass filter with a notch for 400Hz system power-supply noise. Setting the cutoff at 347Hz produced the 400Hz notch. The standard filter (Figure 16A) consists of two subcircuits, an LP section followed by a PP4 section.

In the simplified configuration (Figure 16B), the summing amplifier feedback resistor, R_{Z3} is changed from 10kΩ to 130kΩ and paralleled with a 0.01µF capacitor. Notice that these are the same values used for R_P and C_P in the LP section of Figure 16A. To set correct the summing amplifier gain, resistors, R_{Z1} and R_{Z2} are multiplied by R_P/R_{Z3} (130kΩ/10kΩ). R_{Z1} and R_{Z2} must be greater than 2kΩ to prevent op amp output overloading. If necessary, increase R_{Z1}, R_{Z2}, and R_{Z3} by decreasing C_P.

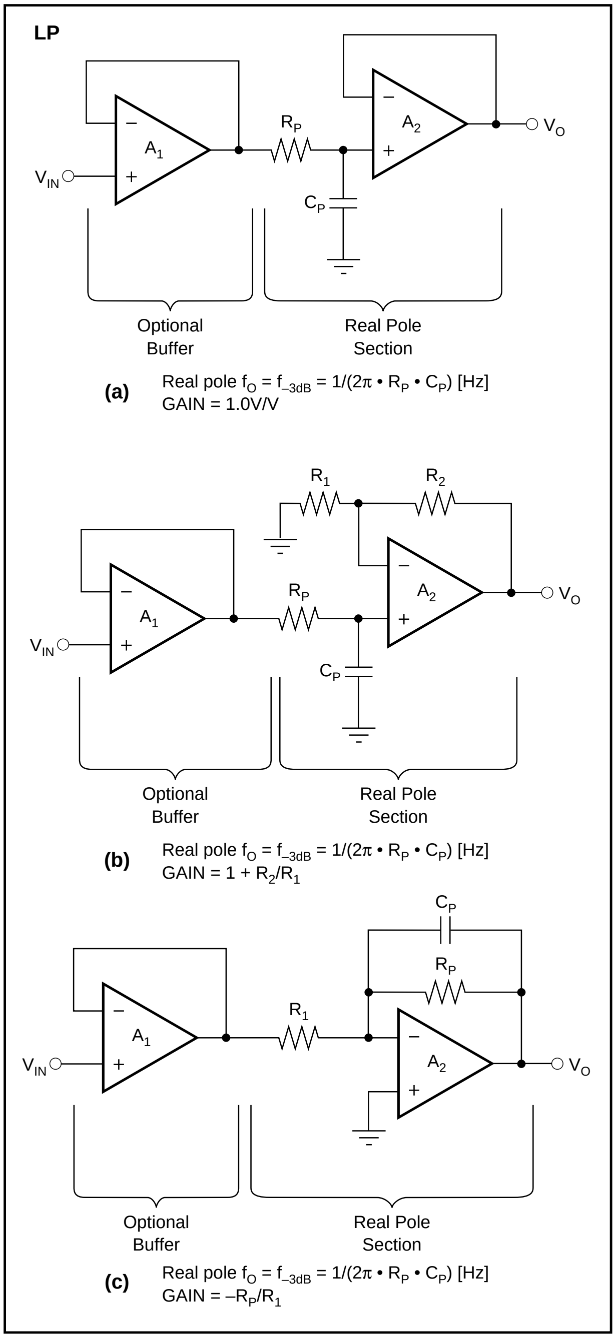


FIGURE 13. Low-Pass (LP) Subcircuit: (a) Basic; (b) with Noninverting Gain; (c) with Inverting Gain.

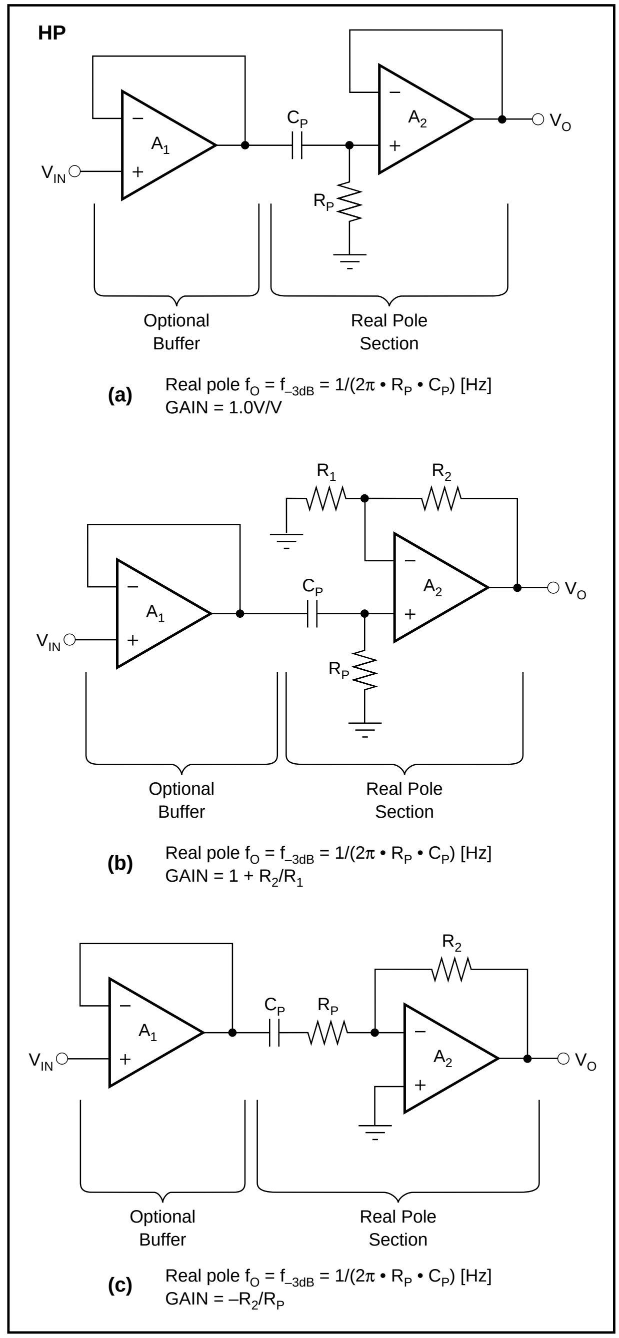


FIGURE 14. High-Pass (HP) Subcircuit: (a) Basic; (b) with Noninverting Gain; (c) with Inverting Gain.

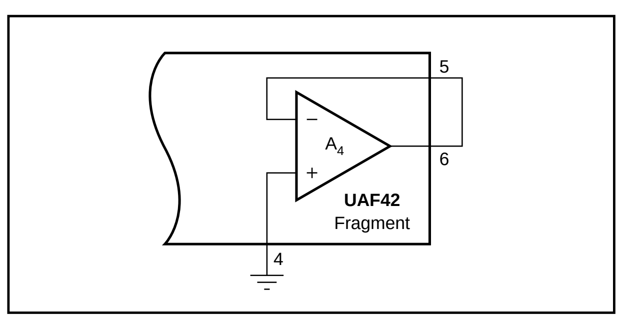


FIGURE 15. Connect Unused Auxiliary Op Amps as Grounded-Input Unity-Gain Followers.

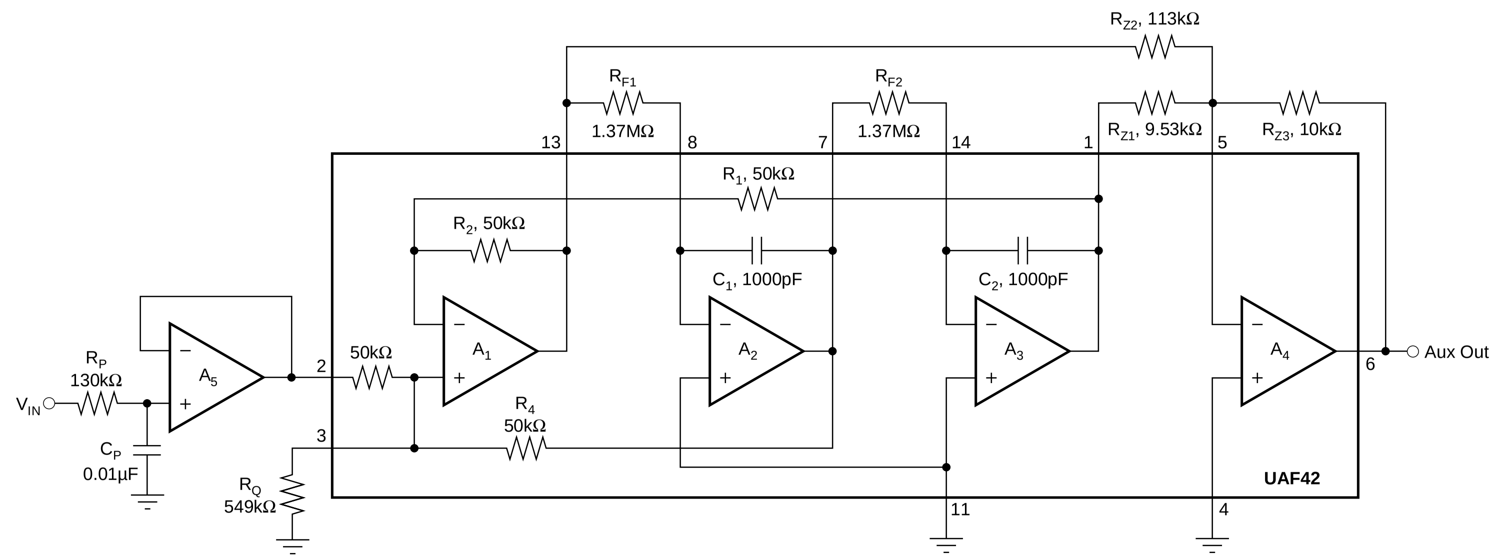
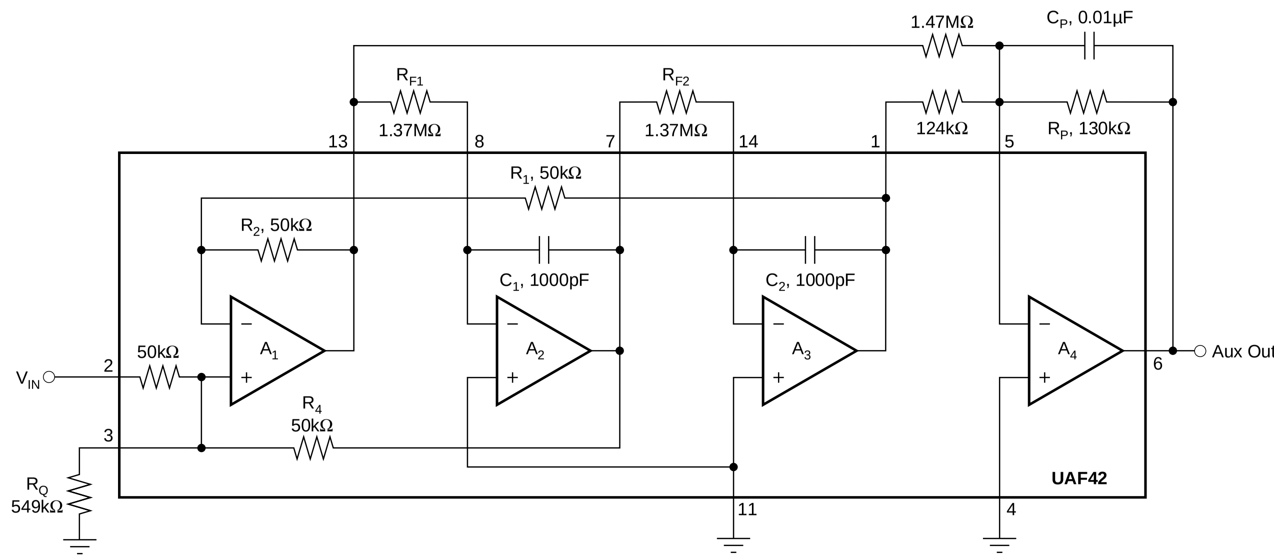


FIGURE 16A. Three-Pole 347Hz Inverse Chebyshev Low-Pass Filter Designed by FilterPro™ Program.



NOTE: To establish a real pole at the proper frequency and set the proper summing amplifier gain, the following changes were made to the pole-pair subcircuit:

R_{Z3} changed to R_P.

C_P added in parallel with R_{Z3}.

R_{Z1} and R_{Z2} multiplied by R_P/R_{Z3}.

FIGURE 16B. Simplified Three-Pole 347Hz Inverse Chebyshev Low-Pass Filter (created by moving real pole to feedback of A_4 and eliminating LP input section).

Q ENHANCEMENT

When the $f_O \cdot Q$ product required for a pole-pair section is above ≈100kHz at frequencies above ≈3kHz, op amp gain-bandwidth limitations can cause Q errors and gain peaking. To mitigate this effect, the program automatically compensates for the expected error by decreasing the design-Q according to a Q-compensation algorithm(1). When this occurs, the value under the Q heading on the *UAF42 Filter Component Values* print-out will be marked with an asterisk indicating that it is the theoretical Q, not the actual design Q. The actual design Q will be shown under an added heading labeled Q_{COMP}.

USING THE FilterPro™ PROGRAM

With each data entry, the program automatically calculates filter performance. This allows you to use a "what if" spreadsheet-type design approach. For example; you can quickly determine, by trial and error, how many poles are needed for a desired roll-off.

GETTING STARTED

The first time you use the program, you may want to follow these suggested steps.

Type **`FILTER42 <ENTER>`** to start the program.

Use the arrow keys to move the cursor to the **Filter Response** section.

1) SELECT FILTER RESPONSE

Press **`<ENTER>`** to toggle through four response choices:

Low-pass
High-pass
Band-pass
Notch (band-reject)

When the desired response appears, move the cursor to the **Filter Type** section.

2) SELECT FILTER TYPE

Move the cursor to the desired filter type and press **`<ENTER>`**. The selected filter type is highlighted and marked with an asterisk. There are four filter-type choices:

Butterworth	Bessel
Chebyshev	Inverse Chebyshev

If you choose Chebyshev, you must also enter ripple (i.e. pass-band ripple—see Chebyshev filter description).

If you choose Inverse Chebyshev, you must also enter A_{MIN} (i.e. min attenuation or max gain in stop-band—see Inverse Chebyshev filter description).

3) ENTER FILTER ORDER

Move the cursor to the **Filter Order** line in the **Parameters** section. Enter filter order **n** (from 2 to 10).

(1) L.P. Huelsman and P. E. Allen, *Theory and Design of Active Filters*, p. 241.

4A) ENTER FILTER FREQUENCY

Move the cursor to the **Filter Frequency** line in the **Parameters** section.

Low-pass/high-pass filter: enter the f_{-3dB} or cutoff frequency.

Band-pass filter: enter the center frequency, f_{CENTER}.

Band-reject (notch) filter: enter the notch frequency, f_{NOTCH}.

If your filter is low-pass or high-pass, go to step 5.

4B) ENTER FILTER BANDWIDTH

If the filter is a band-pass or band-reject (notch), move the cursor to the bandwidth line and enter bandwidth.

If you press **`<ENTER>`** with no entry on the bandwidth line, you can enter f_L and f_H instead of bandwidth. f_L and f_H are the f_{-3dB} points with regard to the center frequency for Butterworth and Bessel filters. They are the end of the ripple-band for Chebyshev types. This method of entry may force a change in center frequency or notch frequency.

5) PRINT-OUT COMPONENT VALUES

Press function key **`<F4>`** to print-out **Filter Component Values** and a **Filter Block Diagram**. Follow the instructions in the filter implementation section of this bulletin to assemble a working filter.

USING THE PLOT FEATURE

A Plot feature allows you to view graphical results of filter gain and phase vs frequency. This feature is useful for comparing filter types.

To view a plot of the current filter design, press **`<F2>`**.

GRAPHIC DISPLAY COMMANDS

While viewing the graphic display, several commands can be used to compare filter responses:

`<F1>` or **S**—***S***aves the plot of the current design for future recall.
`<F2>` or **R**—***R***ecalls the ***S***aved plot and plots it along with the current design.
`<F3>` or **Z**—Plots a ***Z***ero dB reference line.

GRAPHIC DISPLAY CURSOR CONTROL

While viewing the graphics display you can also use the arrow keys to move a cursor and view gain and phase for plotted filter responses.

RESISTOR VALUES

With each data entry, the program automatically calculates resistor values. If external capacitors are needed, the program selects standard capacitor values and calculates exact resistor values for the filter you have selected. The **1% Resistors** option in the Display menu can be used to calculate the closest standard 1% resistor values instead of exact resistor values. To use this feature, move the cursor to the **resistors** line in the **Filter Response** section and press

OP AMP SELECTION GUIDE (In Order of Increasing Slew Rate)

T_A = 25°C, V_S = ±15V, specifications typ, unless otherwise noted, min/max specifications are for high-grade model.

OP AMP MODEL	BW typ (MHz)	FPR (1) typ (kHz)	SR typ (V/µs)	V_{OS} max (µV)	V_{OS}/dT max (µV/°C)	NOISE at 10kHz (nV/√Hz)	C_{CM} (3) (pF)
OPA177	0.6	3	0.2	10	±0.1	8	1
OPA27	8	30	1.9	25	±0.6	2.7	1
OPA2107 dual (2)	4.5	280	18	500	±5	8	4
OPA602 (2)	6	500	35	250	±2	12	3
OPA404 quad (2)	6	500	35	1000	±3 typ	12	3
OPA627 (2)	16	875	55	100	±0.8	4.5	7
UAF42 aux amp (2)	4	160	10	5000	±3 typ	10	4

NOTES: (1) FPR is full power response at 20Vp-p as calculated from slew rate. (2) These op amps have FET inputs. (3) Common-mode input capacitance.

<ENTER>. The program will toggle between **exact resistors** and **standard 1% resistors**.

CAPACITOR SELECTION

Even-order filters above 10Hz normally will not require external capacitors. Odd order filters require one external capacitor to set the real pole in the LP or HP section. Capacitor selection is very important for a high-performance filter. Capacitor behavior can vary significantly from ideal, introducing series resistance and inductance which limit Q. Also, nonlinearity of capacitance vs voltage causes distortion. The 1000pF capacitors in the UAF42 are high performance types laser trimmed to 0.5%.

If external capacitors are required, the recommended capacitor types are: NPO ceramic, silver mica, metallized polycarbonate; and, for temperatures up to 85°C, polypropylene or polystyrene. Common ceramic capacitors with high dielectric constants, such as “high-K” types should be avoided—they can cause errors in filter circuits.

OP AMP SELECTION

Normally you can use the uncommitted fourth op amp in the UAF42 to implement any necessary LP, HP, or gain stages. If you must use additional op amps, it is important to choose an op amp that can provide the necessary DC precision, noise, distortion, and speed.

OP AMP SLEW RATE

The slew rate of the op amp must be greater than $\pi \cdot V_{OPP} \cdot$ BANDWIDTH for adequate full-power response. For example, operating at 100kHz with 20Vp-p output requires an op amp slew rate of at least 6.3V/µs. Burr-Brown offers an excellent selection of op amps which can be used for high performance active filter sections. The guide above lists some good choices.

OP AMP BANDWIDTH

As a rule of thumb, in low-pass and band-pass applications, op amp bandwidth should be at least 50 • GAIN • f_O, where GAIN = noise gain of the op amp configuration and f_O = filter f_{-3dB} or f_{CENTER} frequency.

In high-pass and band-reject (notch) applications, the required op amp bandwidth depends on the upper frequency of interest. As with most active filters, high-pass filters designed with the UAF42 turn into band-pass filters with an upper roll-off determined by the op amp bandwidth. Error due to op amp roll-off can be calculated as follows:

$$\% = 100\left(1 - \frac{1}{\sqrt{(1 + f^2 \cdot (NGAIN)^2/(UGBW)^2)}}\right)$$

or

$$f = \frac{\sqrt{200 - \%} \cdot \sqrt{\%} \cdot UGBW}{NGAIN \cdot (\% - 100)}$$

Where:

% = Percent gain error   f = Frequency of interest (Hz)

NGAIN = Noise gain of op amp (V/V)

= GAIN of noninverting configuration

= 1 + |GAIN| of inverting configuration

UGBW = Unity-gain bandwidth of the op amp (Hz):

GAIN ACCURACY (%)	f (NGAIN)/(UGBW)
–29.29	1.000
–10.00	0.484
–1.00	0.142
–0.10	0.045
–0.01	0.014

EXAMPLES OF MEASURED UAF42 FILTER RESPONSE

Figures 17 and 18 show actual measured magnitude response plots for 5th-order 5kHz Butterworth, 3dB Chebyshev, –60dB Inverse Chebyshev and Bessel low-pass filters designed with the program and implemented with UAF42s. As can be seen, the initial roll-off of the Chebyshev filter is the fastest and the roll-off of the Bessel filter is the slowest. However, each of the 5th-order all-pole filters ultimately rolls off at –N • 20dB/decade, where N is the filter order (–100dB/decade for a 5-pole filter).

The oscilloscope photographs (Figures 19-22) show the step response for each filter. As expected, the Chebyshev filter has the most ringing, while the Bessel has the least.

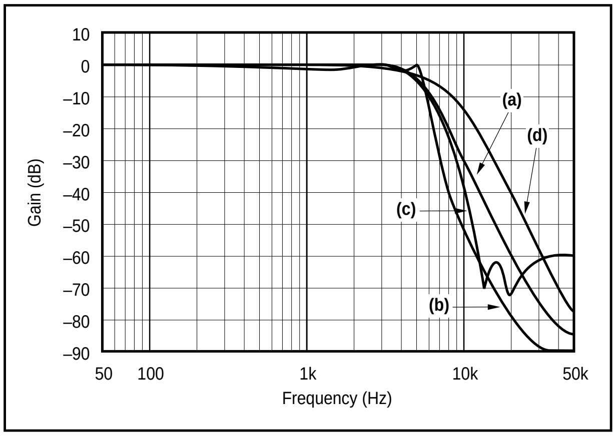


FIGURE 17. Gain vs Frequency for Fifth-Order 5kHz (a) Butterworth, (b) 3dB Chebyshev, (c) –60dB Inverse Chebyshev, and (d) Bessel Unity-Gain Low-Pass Filters, Showing Overall Filter Response.

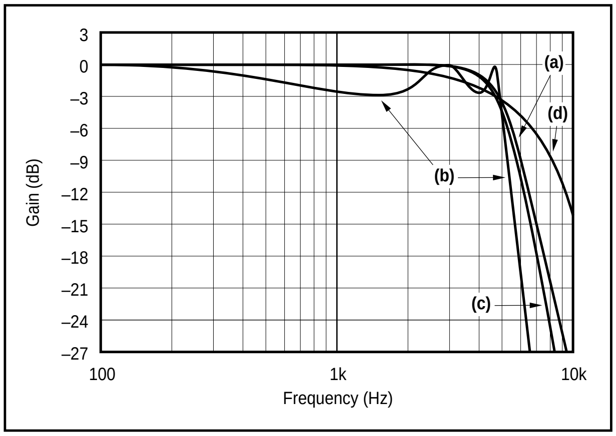


FIGURE 18. Gain vs Frequency for Fifth-Order 5kHz (a) Butterworth, (b) 3dB Chebyshev, (c) –60dB Inverse Chebyshev, and (d) Bessel Unity-Gain Low-Pass Filters, Showing Transition-Band Detail.

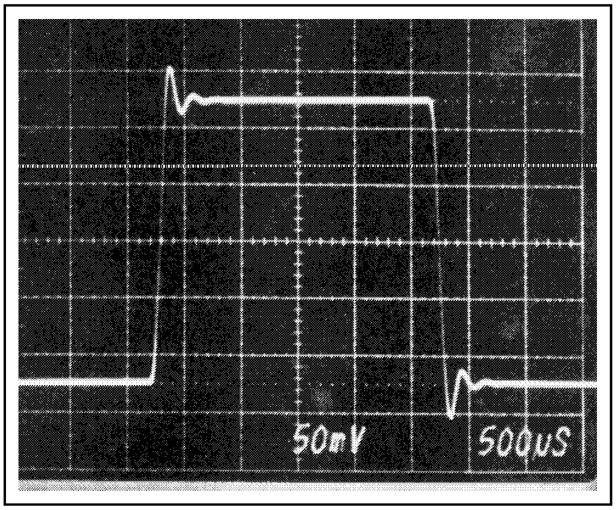


FIGURE 19. Step Response of Fifth-Order 5kHz Butterworth Low-Pass Filter.

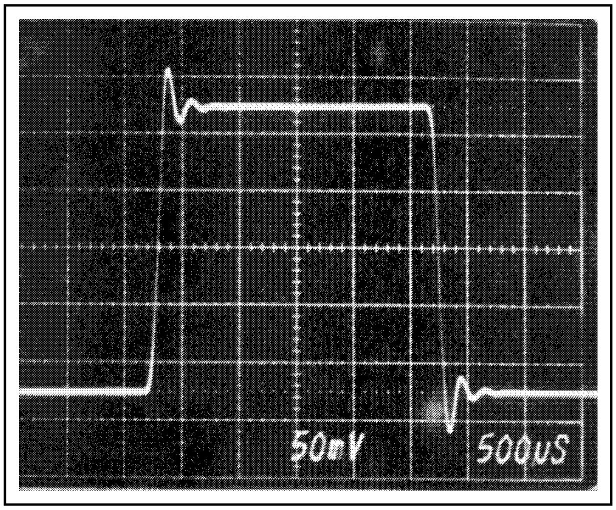


FIGURE 21. Step Response of Fifth-Order 5kHz, –60dB Inverse Chebyshev Low-Pass Filter.

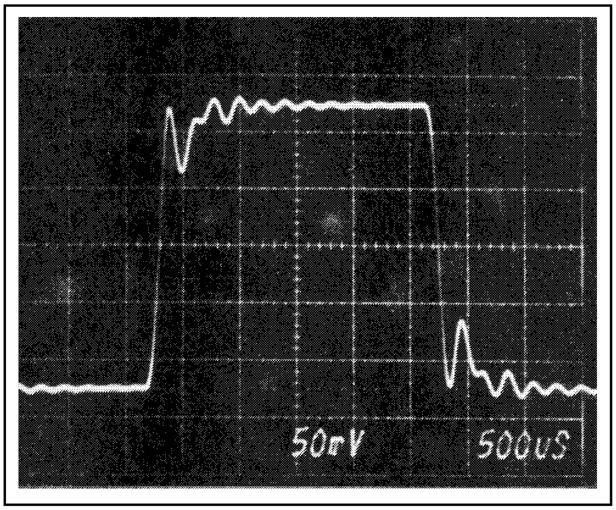


FIGURE 20. Step Response of Fifth-Order 5kHz, 3dB Ripple Chebyshev Low-Pass Filter.

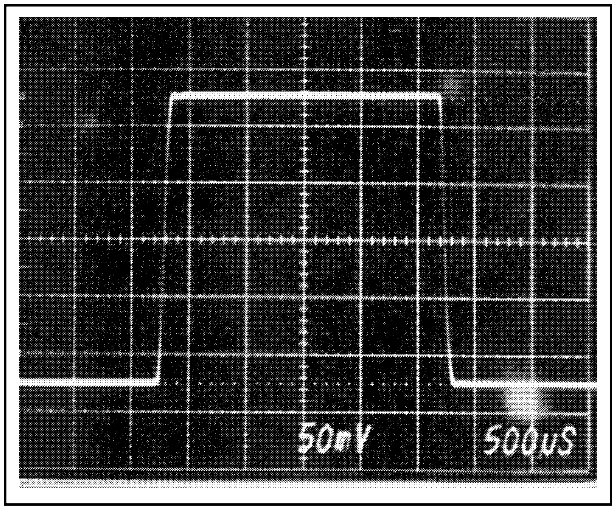


FIGURE 22. Step Response of Fifth-Order 5kHz Bessel Low-Pass Filter.

BURR - BROWN ® APPLICATION BULLETIN
Mailing Address: PO Box 11400 • Tucson, AZ 85734 • Street Address: 6730 S. Tucson Blvd. • Tucson, AZ 85706
Tel: (602) 746-1111 • Twx: 910-952-111 • Telex: 066-6491 • FAX (602) 889-1510 • Immediate Product Info: (800) 548-6132

SIMPLE FILTER TURNS SQUARE WAVES INTO SINE WAVES

by R. Mark Stitt (602) 746-7445

Many signals are digitally generated or transmitted as square waves. It is often desirable to convert these signals into sine waves. For example, the 350Hz, 440Hz, 480Hz, and 620Hz telephone supervisory tones transmitted over fiber-optics may appear at curb-side as square waves. To be used in telephone equipment it is desirable to convert the square waves into low-distortion sine waves. This can be done with a simple filter.

According to its Fourier series, a 50% duty-cycle square wave consists of odd order harmonic sine waves with the fundamental at the same frequency as the square wave.

Fourier Series for a Square Wave

$$\frac{4k}{\pi}\left(\sin x + \tfrac{1}{3}\sin 3x + \tfrac{1}{5}\sin 5x + \cdots\right)$$

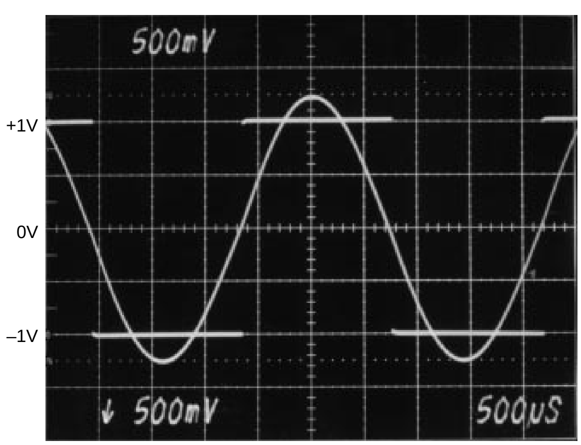
where k = peak amplitude of the square wave

A sine wave with the same frequency as the square wave can be gleaned by filtering out the harmonics above the fundamental. A "tuned-circuit" bandpass filter with a Q of 10 attenuates signals at three times the bandpass frequency by 28.4dB. Since the amplitude of the third harmonic is 1/3 that of the fundamental, the total attenuation of the third harmonic compared to the fundamental is nearly 40dB. The result is a low distortion sine wave as shown in Figure 1A. Notice that although the filter has unity gain, the amplitude of the sine wave output signal is greater than that of the square wave. This is because the fundamental has an amplitude of $4/\pi$ times that of the square wave as shown by the Fourier series. The bandpass filter will also filter out any DC component of the square wave input as shown in Figure 1B.

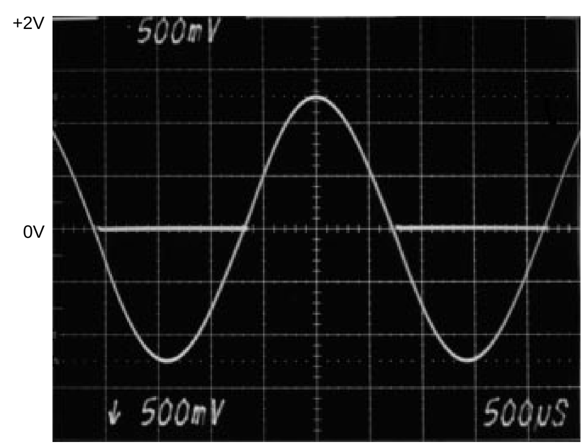
The circuit for a "tuned-circuit" bandpass filter using a Burr-Brown UAF42 universal active filter chip is shown in Figure 2. The UAF42 contains op amps, gain-set resistors, and on-chip precision (0.5%) 1000pF capacitors to form a time continuous filter, free from the anomalies and switching noise associated with switched-capacitor filters. The only external components required are three 1% resistors to set center frequency and Q. In this example, resistors are selected to produce a "tuned-circuit" bandpass filter simulating a tuned-circuit response with 350Hz center frequency and Q = 10. A computer-aided design program, FilterPro, is available free of charge from Burr-Brown to make it easy to design all kinds of active filters using the UAF42.

To design a "tuned-circuit" bandpass filter with Q = 10: load FilterPro FILTER42, select Bandpass filter response, select Order n = 2, set the desired center frequency (f_{CENTER}), and set the bandwidth to 1/10 the center frequency. You can plot the filter response and print out component values.

A fourth, auxiliary, op amp in the UAF42 is available for use in other circuitry. If the auxiliary op amp is not used, connect it as a unity-gain follower with the input to ground (connect –IN to V_{OUT} and +IN to ground).



1a. A square wave passed through a simple "tuned-circuit" bandpass filter produces a low distortion sine wave.



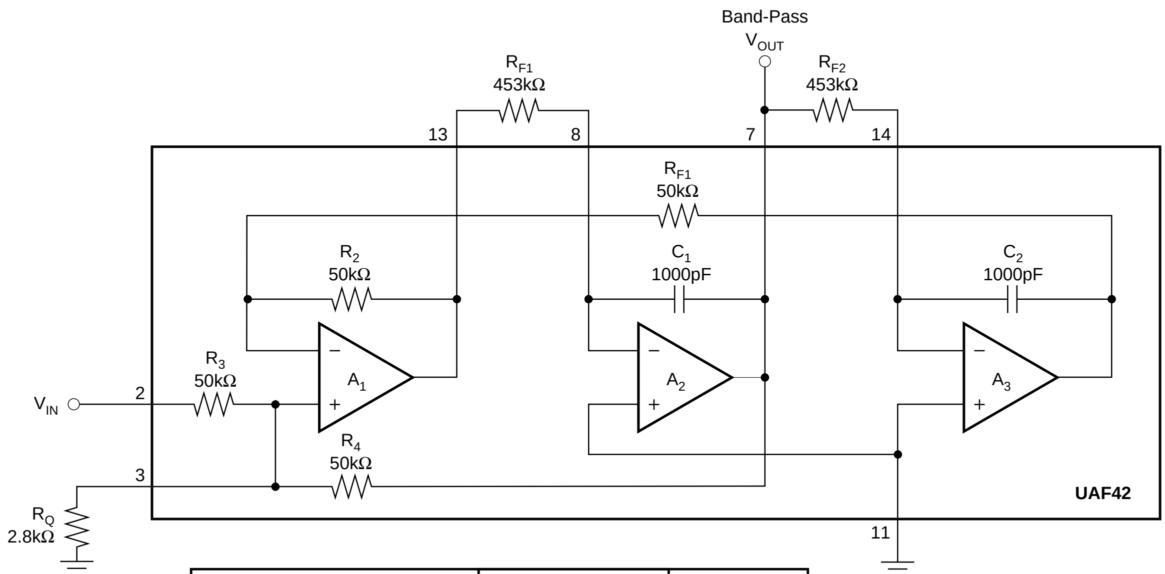
1b. DC components of a square wave passed through bandpass filter are eliminated to produce a low distortion sine wave.

FIGURE 1. Low Distortion Sine Wave.

Printed in U.S.A. December, 1993

Mismatches between the frequency of the input square wave and the center frequency of the bandpass filter will affect the sine wave output. Figure 3 shows measured sine wave output total harmonic distortion (THD) and gain variation for mismatches from 0 to ±5%. A typical mismatch of 1% gives less than 1.5% THD and less than 2% gain deviation.

Variations of the square-wave duty cycle from 50% will also increase distortion due to second-order harmonic content. In applications with a pulse train or other non-50% duty cycle square wave, it may be desirable to place an inexpensive divide by two digital flip-flop ahead of the filter to assure a 50% duty cycle square-wave input.



CENTER FREQUENCY (Hz)	R_{F1}, R_{F2} (Ω)	R_Q (Ω)
350	453k	2.8k
440	365k	2.8k
480	332k	2.8k
620	255k	2.8k

Component values for selected Q = 10 “tuned-circuit” bandpass filters.

FIGURE 2. A Simple 350kHz, Q = 10, “Tuned-Circuit” Bandpass Filter Built with the UAF42 Requires Only Three External Components.

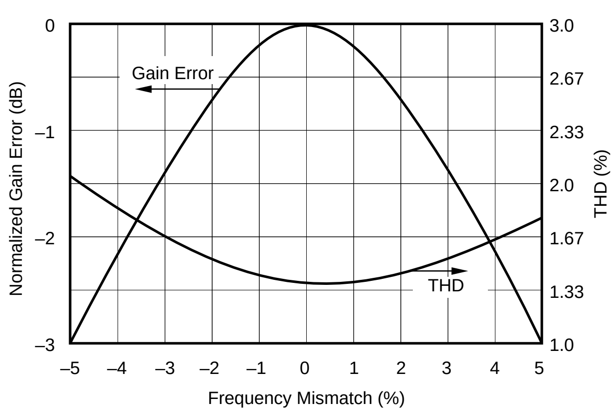


FIGURE 3. Measured Sine Wave Output THD and Normalized Gain Error vs Mismatch between Filter Center Frequency and Square Wave Input Frequency for the “Tuned-Circuit” Bandpass Filter Shown in Figure 2.

IMPORTANT NOTICE

Texas Instruments and its subsidiaries (TI) reserve the right to make changes to their products or to discontinue any product or service without notice, and advise customers to obtain the latest version of relevant information to verify, before placing orders, that information being relied on is current and complete. All products are sold subject to the terms and conditions of sale supplied at the time of order acknowledgment, including those pertaining to warranty, patent infringement, and limitation of liability.

TI warrants performance of its semiconductor products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are utilized to the extent TI deems necessary to support this warranty. Specific testing of all parameters of each device is not necessarily performed, except those mandated by government requirements.

Customers are responsible for their applications using TI components.

In order to minimize risks associated with the customer's applications, adequate design and operating safeguards must be provided by the customer to minimize inherent or procedural hazards.

TI assumes no liability for applications assistance or customer product design. TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right of TI covering or relating to any combination, machine, or process in which such semiconductor products or services might be or are used. TI's publication of information regarding any third party's products or services does not constitute TI's approval, warranty or endorsement thereof.