Application Report

Techniques for Extending the Usable Power Supply Range of the OPA462 High-Voltage Op Amp

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ABSTRACT

The OPA462 high-voltage (HV), precision op amp is designed for applications using dual supply voltages as high as ±90 V, or a single supply of 180 V. Its output is capable of swinging within 3 V to 5 V of the supply voltage rails while delivering as much as 35 mA output current.

Even though this level of HV performance meets the needs of many op amp HV applications, there are times when even higher voltage capability is needed. This application report describes three higher voltage amplifier circuits that can accommodate supply voltages as high as ±180 V (360 V) further extending the usable voltage output range of the OPA462 amplifier to ±150 V (300 V_{pp}). The techniques described may be applied to lower supply-voltage op amps to increases their supply capability using amplifier circuits similar to those presented.

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1 Introduction

In the distant past, first vacuum tubes and then in the not so distant past, discrete high-voltage (HV) bipolar and MOS semiconductors were applied in countless HV amplifier designs. They proved capable of satisfying linear HV amplifier needs for many years. In time the precision and ease of use provided by operational amplifier (op amp) solutions made them a desired option to replace some of the more conventional HV transistor solutions. The very first op amps used vacuum tubes, but had limited applications. Most practical discrete and monolithic op amps in the early decades were designed for ±15 V (30 V) or less, and the availability of higher voltage options was limited. But yielding to the proverb “Necessity is the mother of invention”, op amp designers moved the state of the art forward and worked to develop ever higher voltage op amps.

Burr-Brown introduced the 3580 series of hybrid op amps during the 1970s and 1980s that were capable of being used with power-supply voltages up to ±150 V (300 V). These early HV solid-state op amps used hybrid construction made up of discrete HV transistor and passive component “chips” mounted on a ceramic substrate. They were wire bonded between the chip pads and substrate metallization, and had laser-trimmable thick film resistors. Their maximum output current capabilities were in the 50- to 60-mA range, sufficient for many applications. Many of their electrical parameters were highly precise, but their power dissipation and cost tended to be high, limiting where they could be practically applied. Their packaging in large, 8-pin TO-3 packages often required an external heat sink to dissipate heat. Based on the hybrid high-voltage op amp successes, work moved onward in the development of increasingly higher voltage, smaller monolithic (IC) op amps that could operate with supplies much greater than the common industry standard ±15 V.

Through the 1980s monolithic op amp supplies moved upwards to ±30 V (60 V) for HV op amps, and by the mid 1990s the OPA445 was introduced, which could be powered by ±45 V (90 V). This was followed in the early 2000s by the OPA454, capable of operating with supplies of ±50 V (100 V). More recently the OPA462 was introduced from TI, which operates with supplies up to ±90 V (180 V).

For many HV applications these op amps are well suited, yet the need for even higher voltage op amps continues. Much of this is driven by HV piezoelectric transducer and actuator applications.

Op amp supply voltages climbed as new HV semiconductor processes, designs and package types became more available that could sustain the higher voltage levels. During that time new applications have come on the scene that require increasingly higher voltages, beyond what individual HV op amps are able to handle on their own.

This application report presents three novel HV op amps circuits using multiple op amps or transistors to extend the useable HV range out even further. The OPA462 ±90 V (180 V) HV op amp is used in all three circuits, but the techniques should be applicable to other HV op amps as well. Some minor circuit adjustments will likely be required for other HV op amps because their electrical specifications can be different from the OPA462. These circuit techniques being presented should be useable with lower voltage ±15 V op amps too. Doing so allows their precise electrical performances to be exploited in applications where somewhat higher supply and output voltages are required.

2 Three Op Amp OPA462 HV Solution

Suppose an HV op-amp application requires a 300-V_{pp} output voltage to be developed across its output load. That output voltage is much higher than the absolute maximum supply capabilities of the OPA454 ±60 V (120 V) and OPA462 ±95 V (190 V) listed in their data sheets. Note that relative to ground, the supply *magnitudes* of an op amp can be higher than the rated maximums provided the voltage *across* its power supply pins does not exceed the absolute maximum voltage rating. For example, an OPA462 could be safely operated with V+ = +280 V and V– = +100 V, as the voltage across the supply pins would be 180 V. If this kind of supply arrangement is used, the input and output conditions must remain within the linear operating regions relative to the HV levels applied to the supply pins. The input of the amplifier circuit could not be grounded, for example, as this would appear to the op amp as an input signal 100 V *below* the low rail, far outside the safe operating region.

There are techniques applied in linear circuits that are used to enhance a particular performance characteristic of an amplifier. The techniques tap into a voltage, or current often obtained from the output stage, and then uses it to enhance the performance of an earlier stage in the amplifier. For example, one might access an output stage electrical property to effectively increase the impedance seen at the amplifier input. This technique is often referred to as *bootstrapping*. Bootstrapping will not be used to alter the general electrical characteristics of the OPA462 HV op amp, but instead applied here to increase the output voltage range of an OPA462 circuit so that it is able to provide the stated 300 V_{pp} across the output load.

Figure 2-1 shows a circuit solution that increases the output voltage swing range to 300 V_{pp} and is composed of three OPA462 HV op amps.

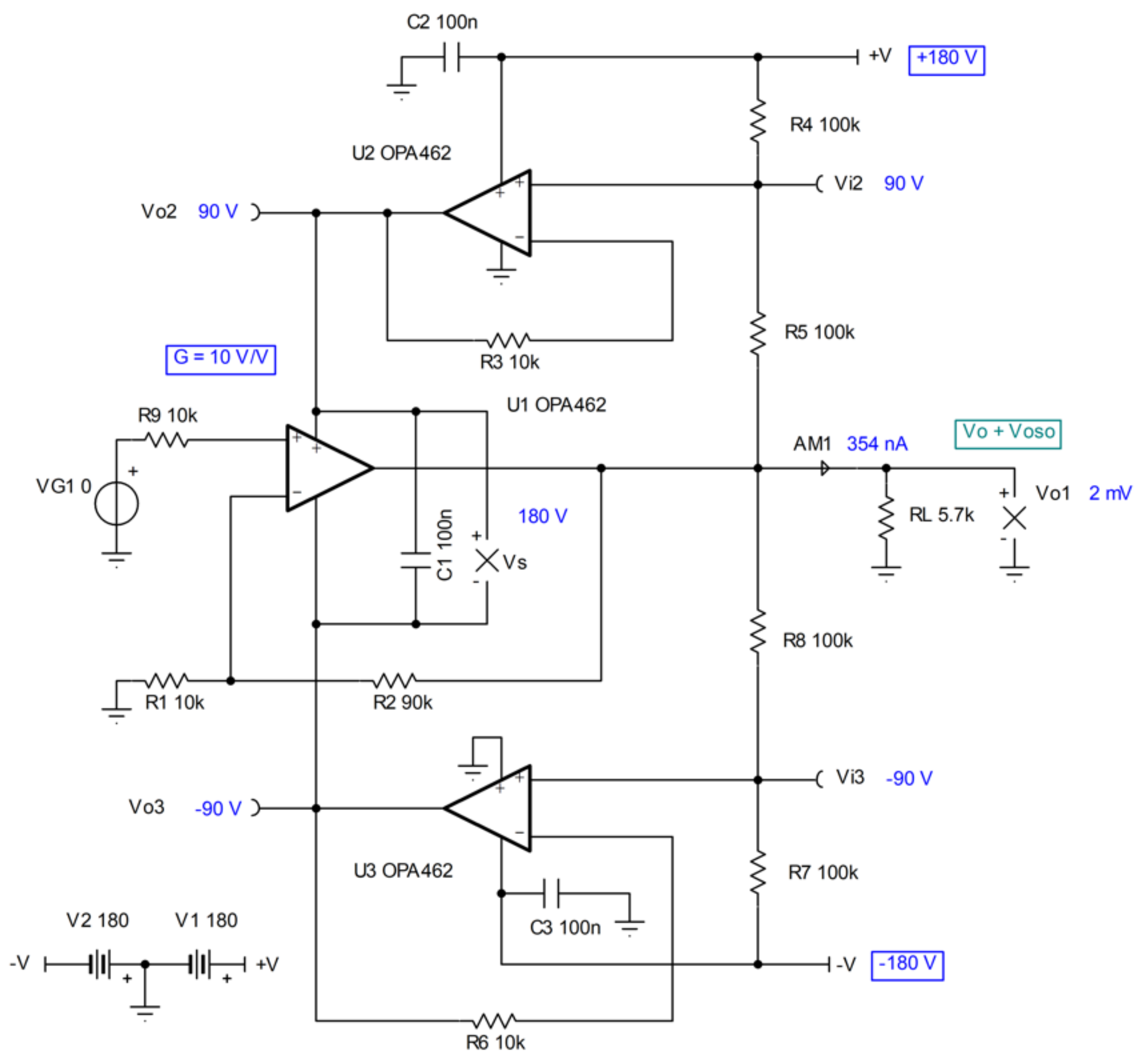

Figure 2-1. Three OPA462 Op Amp HV Solution

Op amp U1, an OPA462 HV op amp, is the signal path amplifier amplifying the input signal provided by signal source VG1. It is set up in this case for a non-inverting gain of +10 V/V. Its closed-loop gain is established from the simple relationship, Av = 1 + (R2 / R1). A 30 V_{pp} input at VG1 results in a 300 V_{pp} output voltage being developed across RL. Although the 300 V_{pp} exceeds the OPA462 absolute maximum supply rating of 190 V, the other two OPA462 op amps U2 and U3 control the supply voltages of U1, keeping them safe and within the maximum rating.

The output pins of the other two OPA462 op amps, U2 and U3, actively drive the V+ and V– supply pins of the U1, and supply its operating current I_Q and the load current it delivers to RL. Each is connected as a voltage follower having a gain of + 1 V/V. Resistive voltage dividers R4, R5 and R7, R8, connected between their associated +V or –V supply line, and the U1 output voltage at any moment establishes the U2 and U3 input voltages. Since the resistors of each divider are equal in the corresponding non-inverting input voltage will be one-half the difference between the HV supply level minus Vo1, divided by two. The voltages developed at the respective U2 and U3 non-inverting input is replicated at each of their outputs.

Shown in Figure 2-1 are the DC voltages occurring at various nodes for the three-op amp circuit. The input applied to U1 is 0 V and the +V and –V supplies are set to ±180 V for this case. The Vo1 output is nearly 0 V, deviating by the output referred voltage offset (Voso) generated by U1 in a gain of +10 V/V. The difference between the +180-V and –180-V power supplies and the U1 output at 0 V, divided by 2 via the resistive dividers, establishes the input of U1 (Vi2) at +90 V and the input at U3 (Vi3) to –90 V. This yields Vo2 at +90 V and Vo3 at –90 V, or +180 V between them. That is the voltage that appears across the supply pins of U1.

In Figure 2-2 the DC input voltage to U1 is first set to +15 V, and then set to –15 V. The node voltages shown in blue correspond to a +15-V input, while the red ones correspond to a –15-V input. Observe how the Vi2, Vo2, Vi3, Vo3 move together as the U1 input voltage changes from the 0 V to –15 V, and then to +15 V. Importantly, observe how the voltage difference across the supply pins of U1 is maintained at +180 V when VG1 set to 0 V, +15 V or –15 V. Additionally, how the output voltage range now extends from +150 V to –150 V, for a 300-V change.

Figure 2-3 shows how the node voltages in the three OPA462 op-amp circuit change as the input voltage is swept linearly from –15 V to +15 V. The difference between the Vo2 and Vo3 voltages is equal to Vs, the voltage across the U1 supply pins. The topmost line in the graph is Vs across the input voltage range. The straight line confirms that Vs remains constant regardless of the output voltage level U1 attains at Vo1.

Noting the supply differences the electrical performances of the three OPA462 op amp HV amplifier are similar to what may be achieved by a single OPA462 operated in the same gain. The power supply rejection (PSR) capability of U1 will be more rigorously exercised because U2 and U3 can change their output voltage rapidly when following the U1 output. This is a different situation compared to when stable, regulated DC supplies are used to power the supply pins of an op amp. The OPA462 has high, power-supply rejection ratio (PSRR) of about 130 dB at DC, 80 dB at 1 kHz ,and 60 dB at 10 kHz, which helps minimize output referred voltage offset changes as the supply voltages of U1 follow its output voltage.

The OPA462 U1 power supply pin bypassing is accomplished in a manner such that U2 and U3 can tolerate the 100-nF capacitance across the U1 supply pins that they drive, without becoming unstable. The capacitor is connected between their outputs. The two op amps are connected as unity gain buffers. They provide a very low output impedance at low frequencies, and supply some of the transient current when demanded by U1. The reactance and impedance of the bypass capacitor decreases as frequency increases, being a more effective bypass at higher frequencies where the output impedance of the op amp is increasing. The combination was found to provide effective bypassing and remain stable in the lab evaluations.

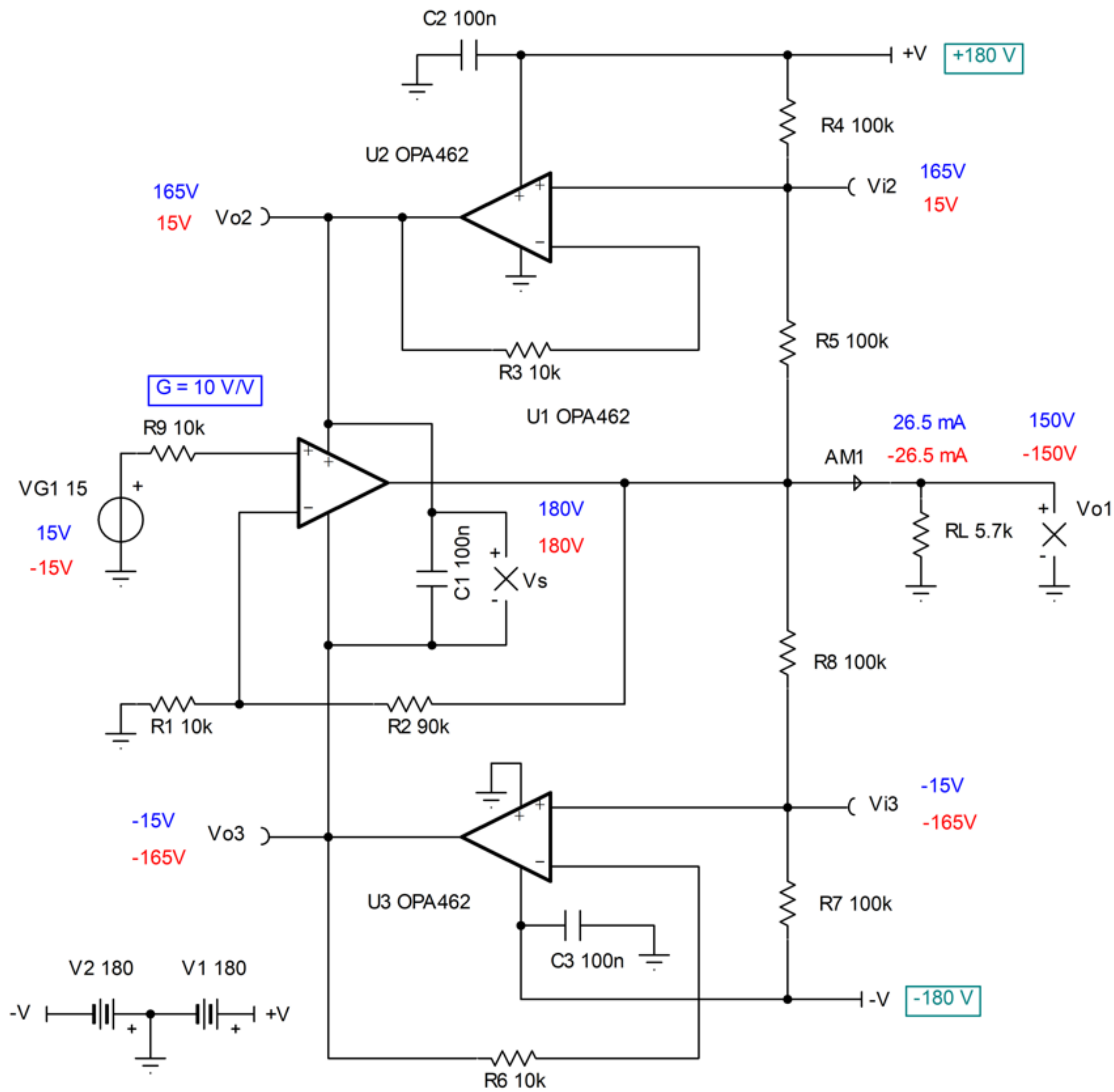

Figure 2-2. Three OPA462 HV Solution With DC Input Voltages of +15 V (Blue) and -15 V (Red)

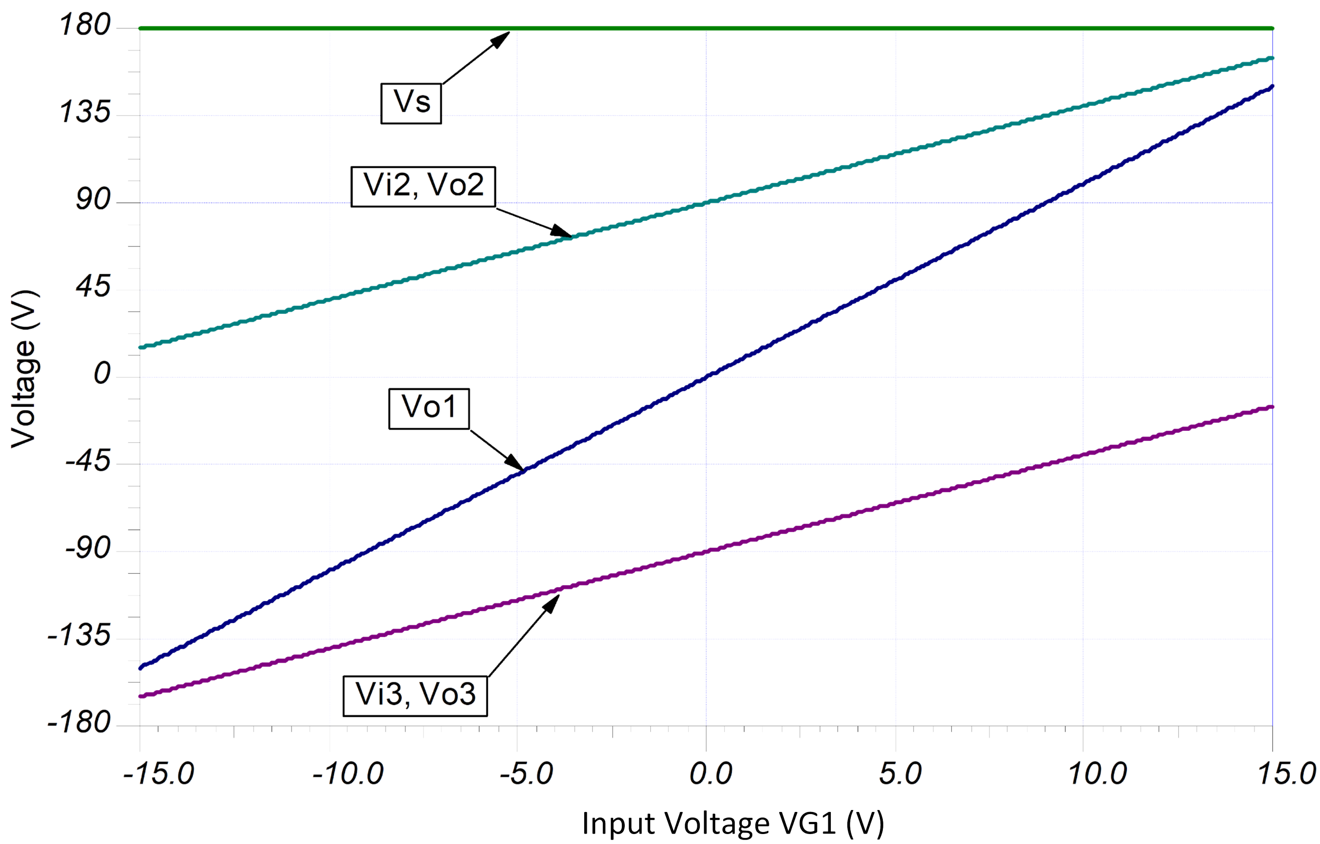

Figure 2-3. Circuit Voltages for the Three OPA462 HV Solutions as the DC Input Voltage VG1 is Swept From –15 V to +15 V

3 Lower Voltage, Lower Cost Three Op Amp Solution

Many op amp designs are not only performance demanding, but cost sensitive as well. That balance was an important consideration for the next OPA462 HV amplifier design. If the maximum supply-voltage range required for U1 can be limited to a maximum of 220 V, a lower cost solution can be realized compared to the three OPA462 solution.

This next design also employs a three op amp bootstrap circuit, but substitutes a lower voltage OPA196 or OPA990 op amp in the U2 and U3 positions formerly held by the two OPA462 HV op amps. These lower voltage op amps provide high DC precision, and offers lower cost compared to when three OPA462 HV op amps are used. The result is a HV amplifier whose maximum output voltage swing is increased by about 30 V to 35 V over that of a circuit using a single OPA462. The HV output capability is about 200 V_{pp} with a 25-mA load current and ±105-V (210 V) supplies. The actual output swing range will be dependent on the output load current being demanded as is the case with all op amps.

Figure 3-1 shows the circuit schematic for this second three op amp HV amplifier design. This amplifier is connected in an inverting amplifier configuration to demonstrate that these bootstrap circuits can be connected as either a non-inverting, or an inverting amplifier.

U1, an OPA462, is again the signal path amplifier as in the first three op amp HV circuit presented. A lower voltage OPA196, or the OPA990 op amps, are used in the U2 and U3 positions to drive the supply rail pins of U1. The circuit functions in the same manner as the first circuit does, but there are significant differences in the voltage levels developed at key circuit points compared to them in the three OPA462 HV circuit.

A goal for the circuit is to achieve a 200 V_{pp} output swing, without exceeding the OPA462 absolute maximum 190-V supply rating and 40-V rating for the OPA196 (42 V for OPA990). This goal can be achieved with the power supplies set to ±105 V by careful circuit planning. The supplies can be increased a bit higher as was done in the circuit presented in Appendix A. However, it is always a best practice to keep the voltage across the U1 several volts below the 190 V maximum to ensure a margin of safety.

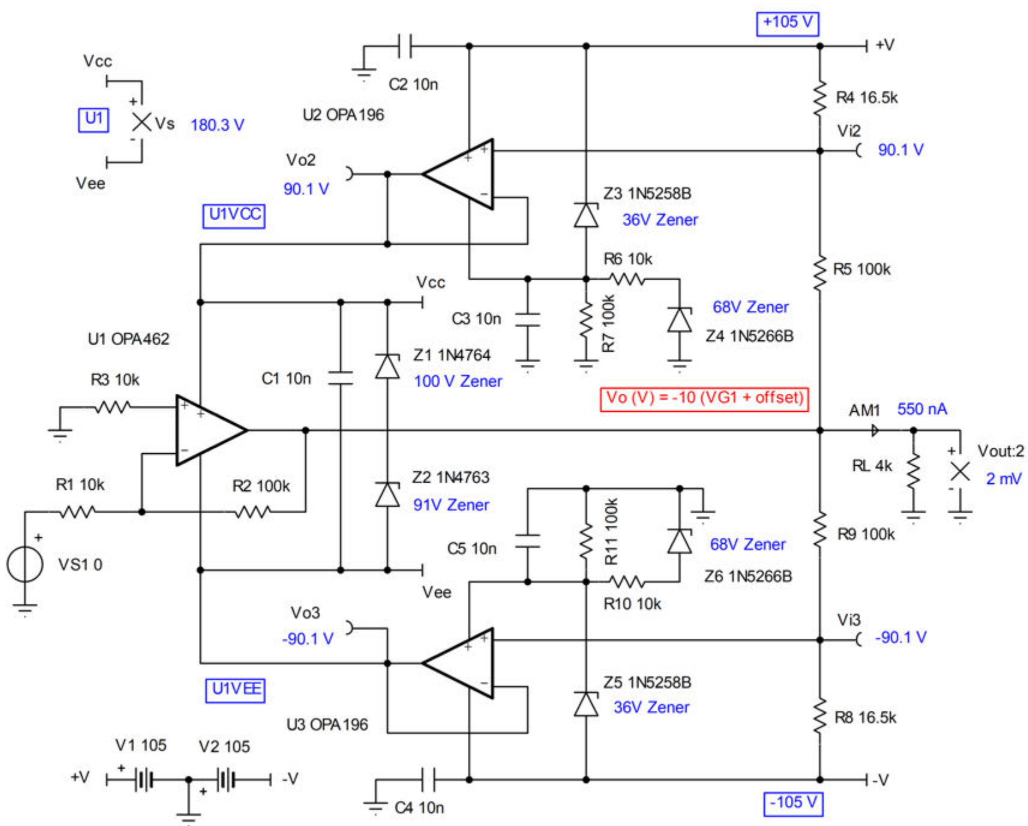

Figure 3-1. 200 V_{pp} Output Solution Achieved by Applying Lower Voltage Op Amps at the U2 and U3 Positions

Similar to the circuits shown in Figure 2-1 and Figure 2-3, a voltage divider is connected from the U1 output to each of the +V and –V power supplies, which are set to +105 V and –105 V, respectively. In this case instead of the dividers establishing a voltage one-half the difference between the supply rail and the U1 output Vo1 level, they establish the voltage across the supply pins of U1 at 180 V. This is evident from schematic points Vi2 and Vi3 which are at +90 V and –90 V, respectively, when the U1 input is at 0 V.

U2 and U3 are configured as buffer amplifiers each having a gain of +1 V/V and the voltage dividers R4, R5 and R8, R9 establish the gain in each current path leading to the supply pins of U1. A gain of 0.14 V/V is established by the divider resistor values shown in Figure 3-1. Additionally, the gain can be determined by dividing the U2 or U3 full output swing voltage by the full U1 output swing required. When the U1 output swings 200 V_{pp}, U2 and U3 each have an output swing of 28 V_{pp} confirming the gain of 0.14 V/V.

The supply voltage for U2 and U3 are each established close to 36 V by the 36-V Zener diodes Z3 and Z5. The 10-kΩ R6 and R10 resistors, and 68-V Z4 and Z6 Zener diodes, provide supply current return paths for U2 and U3.

The Zener and resistor combinations shown in Figure 3-1 provide well-behaved power-up and power-down of the amplifier circuit. It is recommended that low-tolerance Zeners be employed where possible to help set the voltages close to ideal. Five-percent-tolerance Zeners have been available for many decades, and now 2% are common today and are preferred to establish the more critical circuit voltages. Adjustment of R6, R10 and the Z4, Z6 Zener voltage likely would be required if different supply voltages are used. Zener diodes Z1 (100 V) and Z2 (91 V) are added in series with each other and are connected across U1 to provide overvoltage protection.

Figure 3-2 shows how the node voltages move and track as the input voltage is first set to +10 V (blue voltages), and then to –10 V (red voltages). Remember the OPA462 was configured as an inverting amplifier and that is the reason why the output voltage moves opposite to the input polarity.

When considering op amps for U2 and U3 be aware they provide both the DC and AC currents required by U1. That is to say, the DC operating current and any AC current of U1 demanded when driving RL will be sourced from U2 and U3, and thus these drivers must be capable of supplying that current. Any offset, offset drift, or other normal DC errors associated with U2 and U3 will be visible as a small error in the supply levels applied to U1. As a percentage of the supply voltage level, the error will be small.

Additionally, the lab tests performed with U2 and U3 as either the OPA462 or OPA196 indicated improved large-signal dynamic performance may be observed with this configuration, compared to just an OPA462 operating alone. This improvement is attributable to the inputs, outputs and supplies tracking each other across the output swing range. When that is the case, less current is needed to charge internal capacitances, and enhanced slewing performance can result.

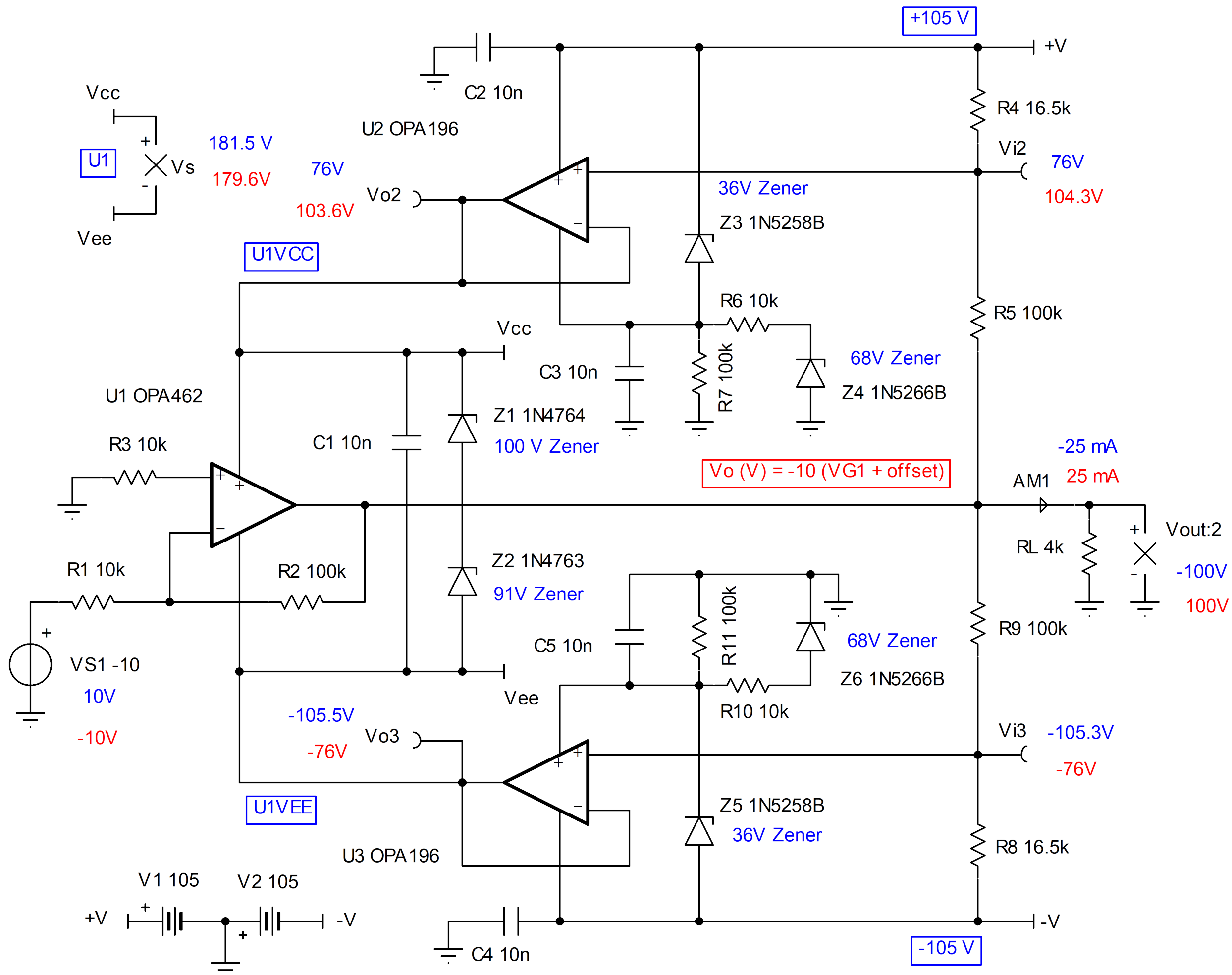

Figure 3-2. OPA462 HV + OPA196 Solution With Input Voltages of +10 V (Blue) and –10 V (Red)

A point to keep in mind with this three op amp circuit is that the U2 and U3 op amps must be individual op amps, and not the dual versions. U2 and U3 need to be electrically isolated from each other and cannot share a common substrate as a dual op amp does. Each requires its own separate power supply pins as the schematics indicate. Therefore, the OPA2196 and OPA2990 cannot be used here.

4 OPA462 300 V_{pp} Output Solution With Discrete Transistor Supply-Rail Drivers

Certainly, cost and complexity are always considerations in any design. The next solution aims at reducing both while maintaining the high performance of the OPA462 as the signal amplifier. If the OPA462 U2, U3 rail drivers can be replaced with low-cost discrete HV bipolar transistors, or HV MOSFETS, a simpler, lower cost 300-V_{pp} output solution may be realized.

Life teaches us "there is no such thing as a free lunch" and in this case for a lower cost solution that old phrase lends merit. This circuit applies discrete transistors in place of the op amps at U2 and U3. Like the op amps, the transistors function as voltage followers, but lack the local feedback and rejection characteristics (PSRR, CMRR) op amps exhibit and employ to enhance precision circuit performance. These op amp electrical characteristics are responsible for reducing errors to very low levels and that is not the case for the simple discrete replacements. Although the discrete followers work well in this third circuit implementation the price to be paid is in less precise DC performances.

High-voltage MOSFETs, bipolar transistors, and Darlington bipolar transistors were all considered as supply-rail driver replacements for the U2 and U3 op amp circuit positions. When the electrical aspects of the supply-rail drivers were fully considered and tested, the HV Darlington transistors were found to provide both ease of use and highly predictable electrical performance. This is not implying conventional HV bipolar transistors and MOSFETS are not usable, it simply was observed that the Darlington's performance on the bench more closely followed the theoretical and simulated performances than was the case for the other types of transistors.

Darlington transistors have an advantage of much higher current gain (β) than conventional transistors. Simplistically, it is like two cascaded transistors connected base-emitter driving another base-emitter where the total β_T equals $\beta_1 \times \beta_2$. If $\beta_1 = \beta_2$, then β^2 results. That significantly decreases the base current (Ib) that flows through the output resistor dividers and results in a more predictable voltage at the resistor divider points Vi2 and Vi3. The HV MOSFETs, while presenting extremely high impedance to the dividers, can have a widely varying gate-to-source threshold voltage (V_{TH}) from one device to the next. Additionally, the availability of HV, low-current MOSFETs is quite limited and their drain-to-source ON resistance $R_{DS(ON)}$ tends to be high compared to their high-current counterparts. High $R_{DS(ON)}$ can result in a larger voltage drop across the drain to source of the MOSFET that reduces the voltage at the U1 supply pins when maximum output current is required by the load.

A good choice for the high-voltage Darlington transistors well suited for this HV op amp application are manufactured by Diodes Incorporated, the ZXTN04120HFF NPN and ZXTP05120HFF PNP. Both have a BV_{CEO} > 120 V. The op amp circuit power supply should be kept to a maximum of about ±155 V when the full swing of the OPA462 output range and the 120 V BV_{CEO} are both taken into full consideration.

The basic design using a Darlington bipolar transistor for the OPA462 supply pin driver is seen in the Figure 4-1 partial circuit schematic. The NPN Darlington transistor T1 is connected as an emitter follower providing the supply voltage to the Vp pin of the U1. A complementary PNP Darlington is employed at its Vn pin.

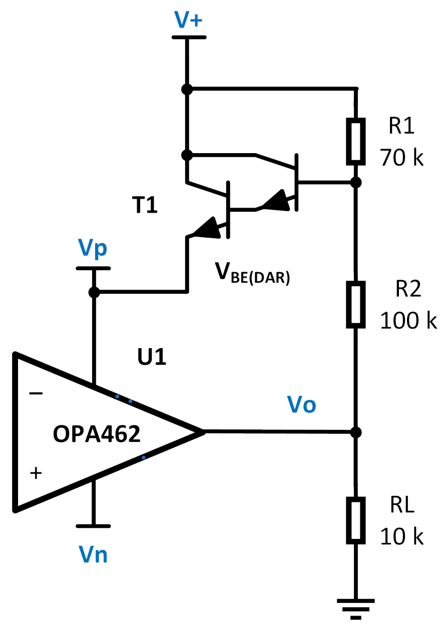

Figure 4-1. Darlington Transistor Driver for U1 OPA462 Positive Supply pin

The voltage appearing at the OPA462 positive supply pin Vp is determined from the loop equation:

$$Vp = [(V_+ - V_O)\left(1 + \frac{R_1}{R_2}\right)^{-1}] - V_{BE(DAR)} \tag{1}$$

Where $V_{BE(DAR)}$ is the sum of the V_{BE} voltage of the two integrated transistors that make up the Darlington transistor.

If the desired value for Vp is decided upon, then Equation 1 can be rearranged to provide resistor values for R_1 or R_2. To find R_1, select a value for R_2 that sets the V_o to midscale, or in this example 0 V. A 100-kΩ resistor value is a practical value for R_2 in this application circuit. Then calculate R_1 from:

$$R_1 = R_2\left[\left((V_+ - V_O) \div \left(V_P + V_{BE(DAR)}\right)\right)\right] - 1 \tag{2}$$

For example, if the desired V_+ is 90 V, Vp is 155 V, R_2 is selected to be 100 kΩ, and with $V_{BE(DAR)}$ approximated to be 1.4 V, then R_1 derived from Equation 2 is:

R_1 = 1 × 10^5 Ω [((155 V – 0 V) / (90 V + 1.4 V)) – 1 V] = 69.6 × 10^4 Ω ≈ 70 kΩ

The Darlington PNP complement to the NPN in Figure 4-2 circuit is used to create Vn. Vn is created in the same way as Vp, but instead utilizing the negative polarities:

$$Vn = [(V_- + V_O)\left(1 + \frac{R_1}{R_2}\right)^{-1}] + V_{BE(DAR)} \tag{3}$$

The two simple Darlington voltage followers develop and provide a reasonably constant 180 V across the OPA462 U1 supply pins. Bench measurements indicate that the voltage control is not quite as tight as with the U2, U3 op amp circuits, but it is completely satisfactory for many applications.

Figure 4-2 shows a practical application of a high-voltage amplifier circuit where the Darlington transistors provide the supply voltages and current to U1, the OPA462 signal amplifier.

Observe that the OPA462 supply pins do not have the commonly included power supply bypass capacitors from the Vp and Vn pins to ground. Instead, bypassing is primarily accomplished by a 10-nF capacitor is connected between the NPN and PNP Darlington transistor bases whose emitters drive the supply pins of U1.

The base-to-base capacitance of the capacitor becomes multiplied by the Darlington's β_T. The result is an equivalent capacitance across the supply pins of the U1 that is $\beta_T \times C$, or several thousand times the 10-nF value of the capacitor. The equivalent capacitor exhibits a very low impedance across the U1 supply pins down to low frequencies. Additionally, the impedance looking into the Darlington transistor emitter followers is very low and that parallels the very low reactance of the equivalent capacitor. The net result is a very low impedance supply bypass effective to very low frequencies.

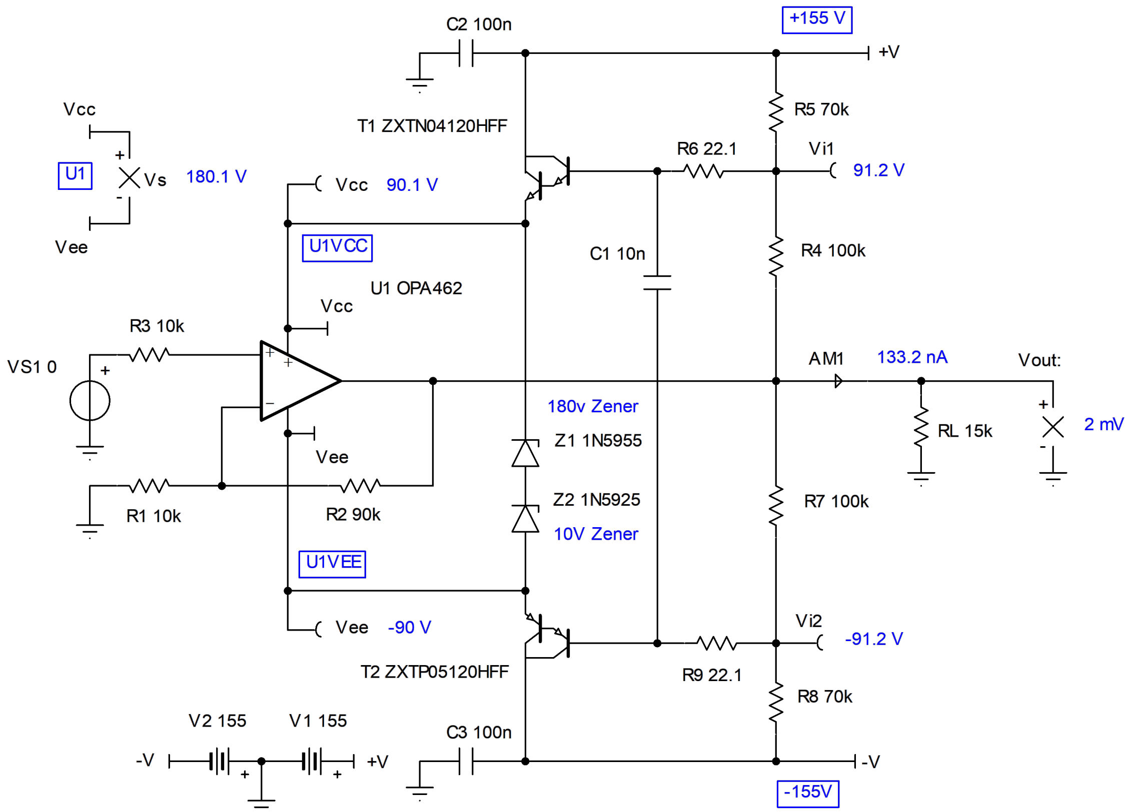

Figure 4-2. Darlington Transistor Supply-Rail Drivers for OPA462, 310-V Total Supply

A TINA Spice circuit simulation with ±155-V supplies yields base voltages of 91.2 V for the NPN, and –91.2 V for the PNP when the output voltage of the U1 is at 0 V. The Darlington transistor emitters are two base-emitter drops below and above their bases at 90.1 V for the NPN, and –90 V for the PNP. This configuration results in 180 V across the supply pins of U1. Like the previous two circuits, the supply pins of U1 track with the U1 output voltage level.

5 Lessons Learned from the Practical Implementation of the HV Op Amp Solutions

The OPA462 HV circuits presented have been built and tested in our TI Precision Amplifiers Applications lab. Appendix A provides the measured results for each circuit The circuits in the general description section and those shown in Appendix A have some minor differences that can include different closed-loop gain settings, some component value differences and numbering, and added HV protection to assure reliable long-term operation. HV circuits may be subjected to transient conditions that could damage the op amps if external protection is not included in the circuits.

Additionally, the OPA462 HV op amp has an enable/shutdown function that can be selected to place the op amp in normal op amp mode, or to shut down the output stage when operation is not required. In the latter case, the operating current is highly reduced. The enable/shutdown pin needs to be properly biased to assure one state of operation or the other. The *OPA462 High-Voltage (180-V), High-Current (30-mA) Operational Amplifier Data Sheet* provides complete information how to apply and configure the enable/shutdown function.

When the OPA462 is applied alone, and not one of the HV boot-strap circuits, the enable/shutdown pin can be left floating. It has a “weak” internal current source that pulls the pin high, enabling the output stage. However, when the OPA462 is used in an HV boot-strap circuit where the supply pins move along with the output, it is recommended that the op amp be set in enable mode. A strong external bias source such as a resistive voltage divider, or low impedance voltage source, is ideal. It was observed in bench tests that circuit noise coupled to the high impedance enable pin could actually unintentionally and momentarily shut down the OPA462 output during a noisy period.

A Appendix

A.1 Overview

This appendix shows the test setup used for hardware evaluation of the bootstrapped circuits and presents the test results in greater detail. Some of the circuit components, component numbers, gain setups, and operating conditions may be somewhat different than used in the discussion portion of the applications report. This was done as a matter of convenience. It does not alter the fundamental circuit topologies or the manner in which they function.

A.2 Summary of Results

Table A-1 summarizes the supplies and noninverting gain used for testing each of the three bootstrap circuit variants. Input and output magnitudes are reported for a 1-kHz sinusoidal input signal. More detailed results are shown in the individual section of each circuit. The input signal magnitudes were chosen by increasing the input signal amplitude until distortion or clipping was visible at the output, then backing off until that distortion/clipping was no longer apparent. Note that each circuit was also tested and shown to perform well in the inverting gain configuration; those results are not shown purely for the sake of brevity.

Table A-1. Supplies and Noninverting Gain Used for Test

Circuit - U1 Supply Rail Sources	HV OPA462 Op Amp at U2 and U3	LV OPA196 Op Amp at U2 and U3	Complimentary NPN-PNP Darlington Transistors
Supplies	360V (±180 V)	220V (±110 V)	310V (±155 V)
Input Magnitude (1-kHz Sinusoid)	5.1 Vpp	4 Vpp	3.08 Vpp
Nominal Gain (Non-inverting)	66 V/V	51 V/V	96.5 V/V
Output Magnitude (1-kHz Sinusoid)	344 Vpp	206 Vpp	298 Vpp
Maximum Tested Load R_L	5.74 kΩ	4 kΩ	5.65 kΩ

A.3 Test Setup and Equipment

Figure A-1 shows the benchtop test setup.

WARNING
Exercise extreme caution when working with high voltages! Injury or death could result from improper handling or usage of high-voltage circuits.

The HV circuits are enclosed in an HV interlock box that has safety switches which trip to turn off the HV power when the lid to the box is opened.

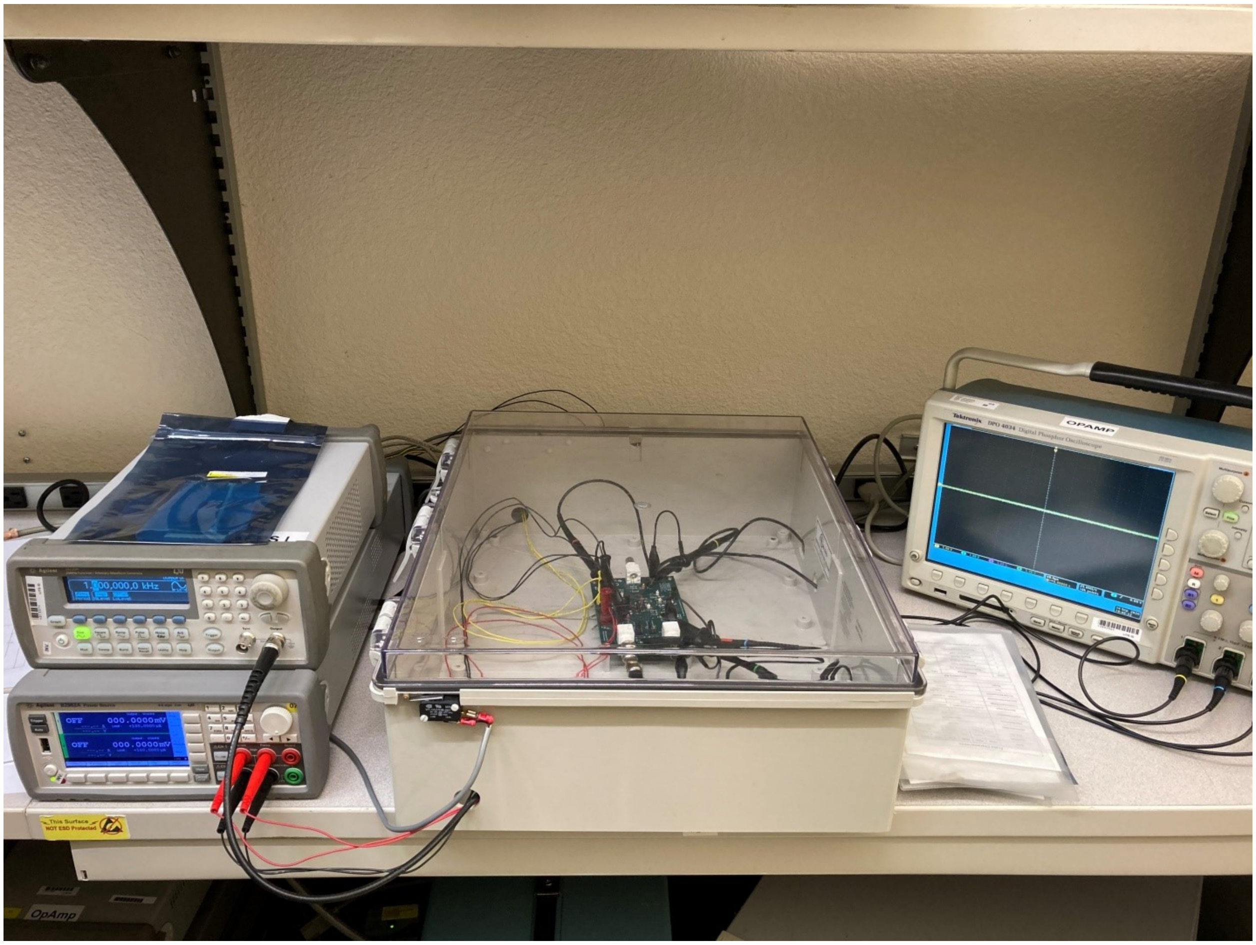

Figure A-1. Benchtop Test Setup

A.4 Printed Circuit Boards

The schematic used in testing each circuit is shown in the appropriate section. A custom PCB was created for each of the designs, reducing the parasitics associated with breadboarding or other prototyping techniques. As an example, Figure A-2 shows one of the test boards built for the *OPA462 Rail Drivers* design. Jumpers permitted quick and easy reconfiguration of the board between tests.

Please note that Texas Instruments does not make available finished PC board assemblies, PC boards or the artwork for these test PCBs. These were developed for our internal use only.

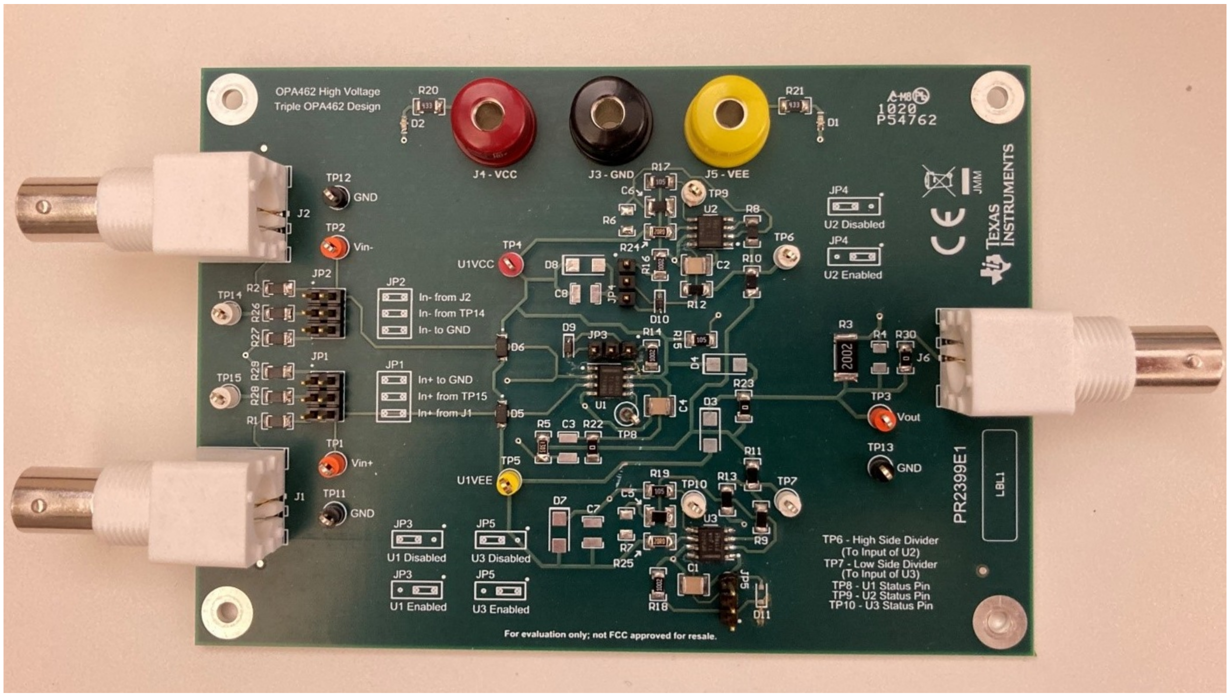

Figure A-2. Example Test PCB Development for OPA462 Three Op Amp Rail Drivers Circuit

A.5 Power Supply, Source Measurement Unit (SMU)

An Agilent B2962A or B2912A was utilized as the HV power supply for all of the hardware testing. Custom cables with insulated banana jacks were created to carry power from the supply or SMU to the test board. Any exposed HV connections (such as the banana jacks that plugged into the actual board) were contained within a high-voltage interlock box. For safety, the interlock lid was monitored via a switch connected to the supply or SMU, such that when the interlock lid was opened the supply or SMU output was automatically disabled.

A.6 Arbitrary Waveform Generator (AWG)

An Agilent 33220A or HP 33120A were utilized to generate the input test signals. The AWG was connected to the test board via a BNC cable with a 50-Ω BNC feedthrough terminator at the board input jack.

A.7 Oscilloscope

The oscilloscope used was a four-channel Tektronix DPO-4034. The 1M Ω||13-pF input settings were used on all channels to tolerate input voltage spikes up to 250 V_{RMS}. The x10 probe attenuation settings were used when measuring the supply rail and output voltages to keep the measurements within the viewable area. It should be noted that this reduces the SNR of the scope by 20 dB because the signal is attenuated, but the system measurement noise is not.

A.8 Circuit 1: OPA462 Three op amp Solution

A.8.1 Schematic

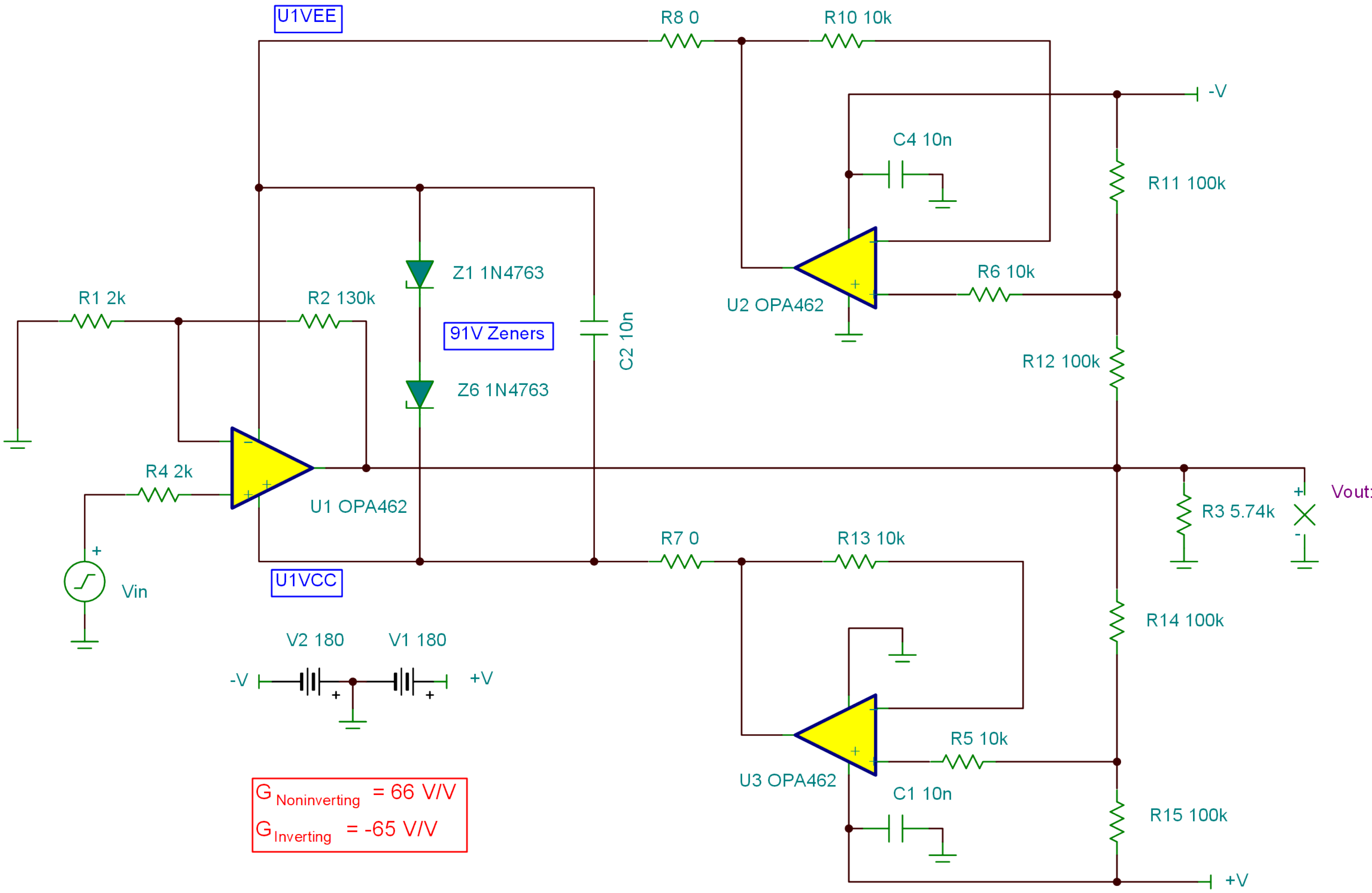

Figure A-3. Three OPA462 Three op amp Solution Schematic

A.8.2 Conventions

Channel 1 is the U1 output.

Channel 2 is the U1 noninverting input.

Channel 3 is the U1VCC rail.

Channel 4 is the U1VEE rail.

A.8.3 Results

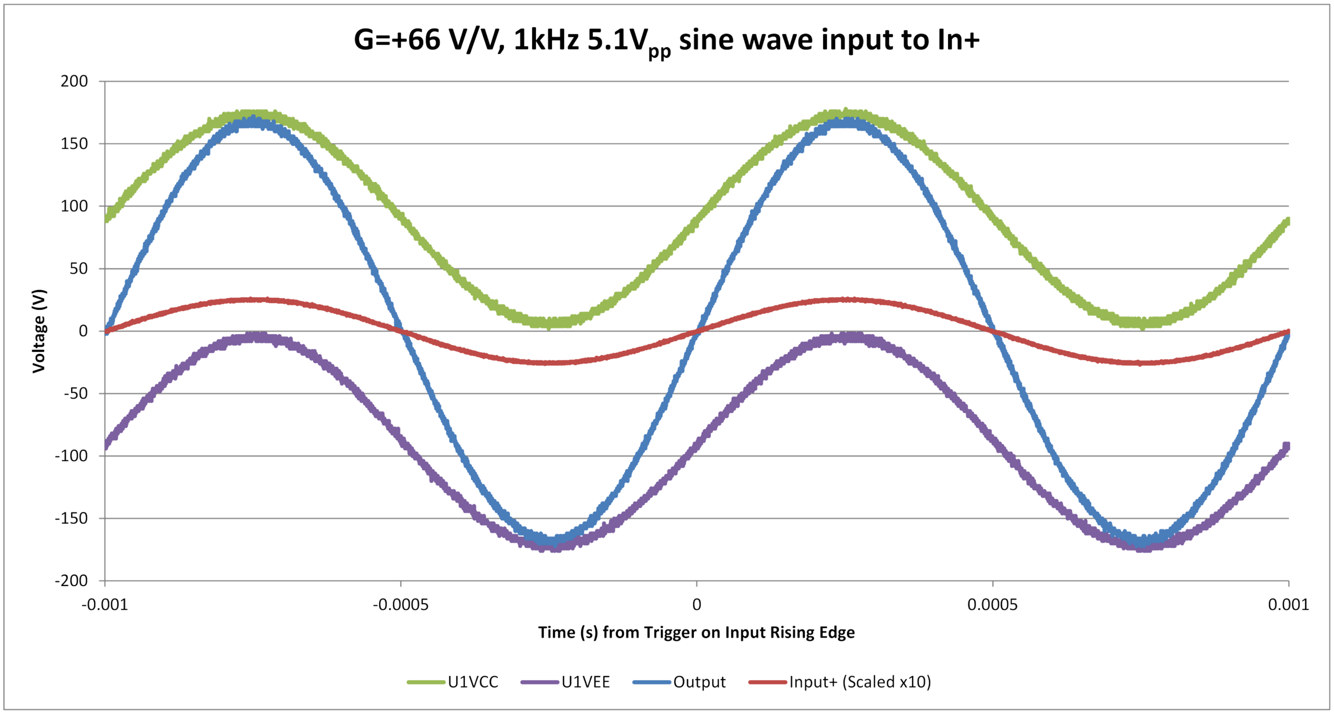

Figure A-4. Noninverting Configuration, G = +66 V/V, 1-kHz Sine Wave (Output 344 V_{pp})

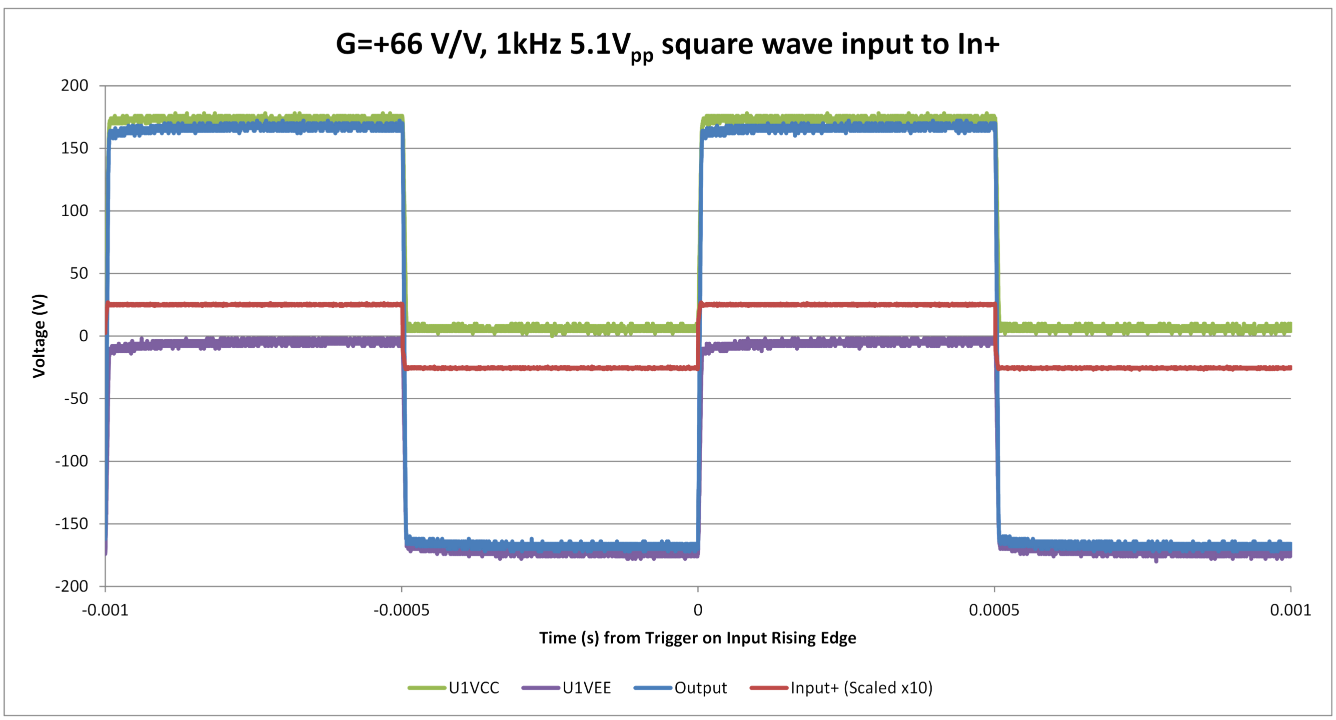

Figure A-5. Noninverting Configuration, G = +66 V/V, 1-kHz Square Wave (Output 344 V_{pp})

Figure A-6 and Figure A-7 show the falling and rising edges of the above square wave waveform, but at a higher zoom level. Please note that the actual values of Channels 1, 3, and 4 are 10 × greater than the image implies, due to the attenuation settings of the scope probes.

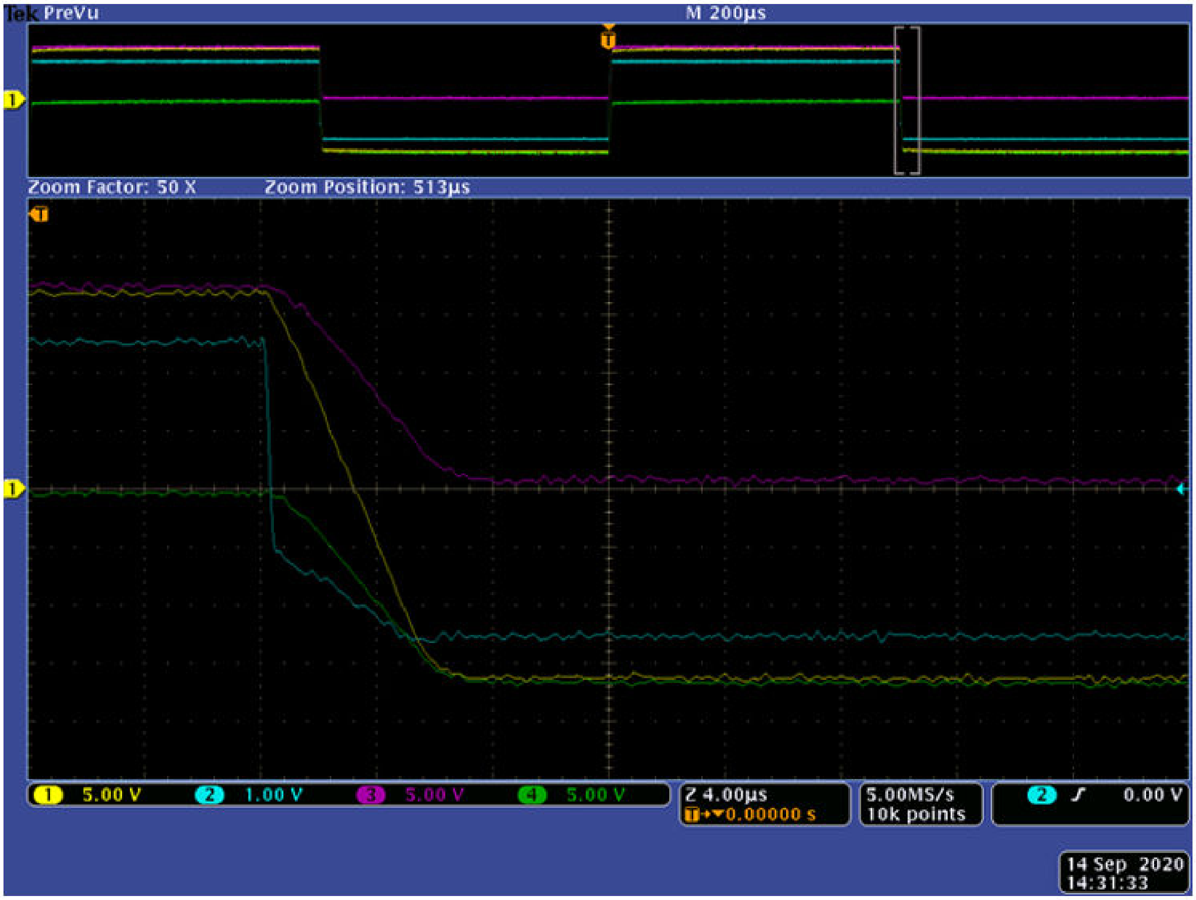

Figure A-6. Noninverting Configuration, G = 66 V/V, 1-kHz Square Wave (5.1 V_{pp}), Zoom on Falling Edge

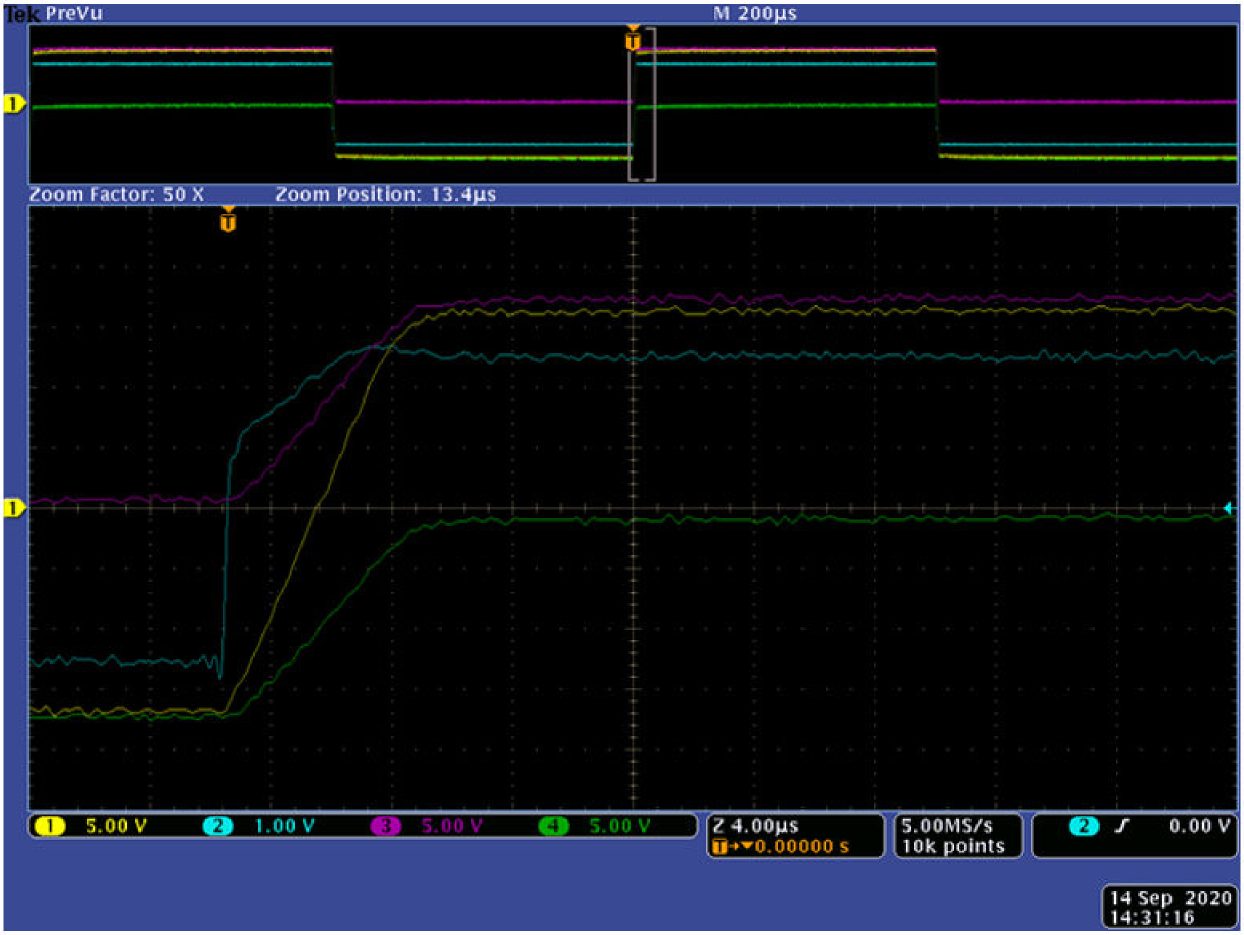

Figure A-7. Noninverting Configuration, G = +66 V/V, 1-kHz Square Wave (5.1 V_{pp}), Zoom on Rising Edge

A.9 Circuit 2: Lower Voltage, Lower Cost Three Op Amp Solution

A.9.1 Schematic

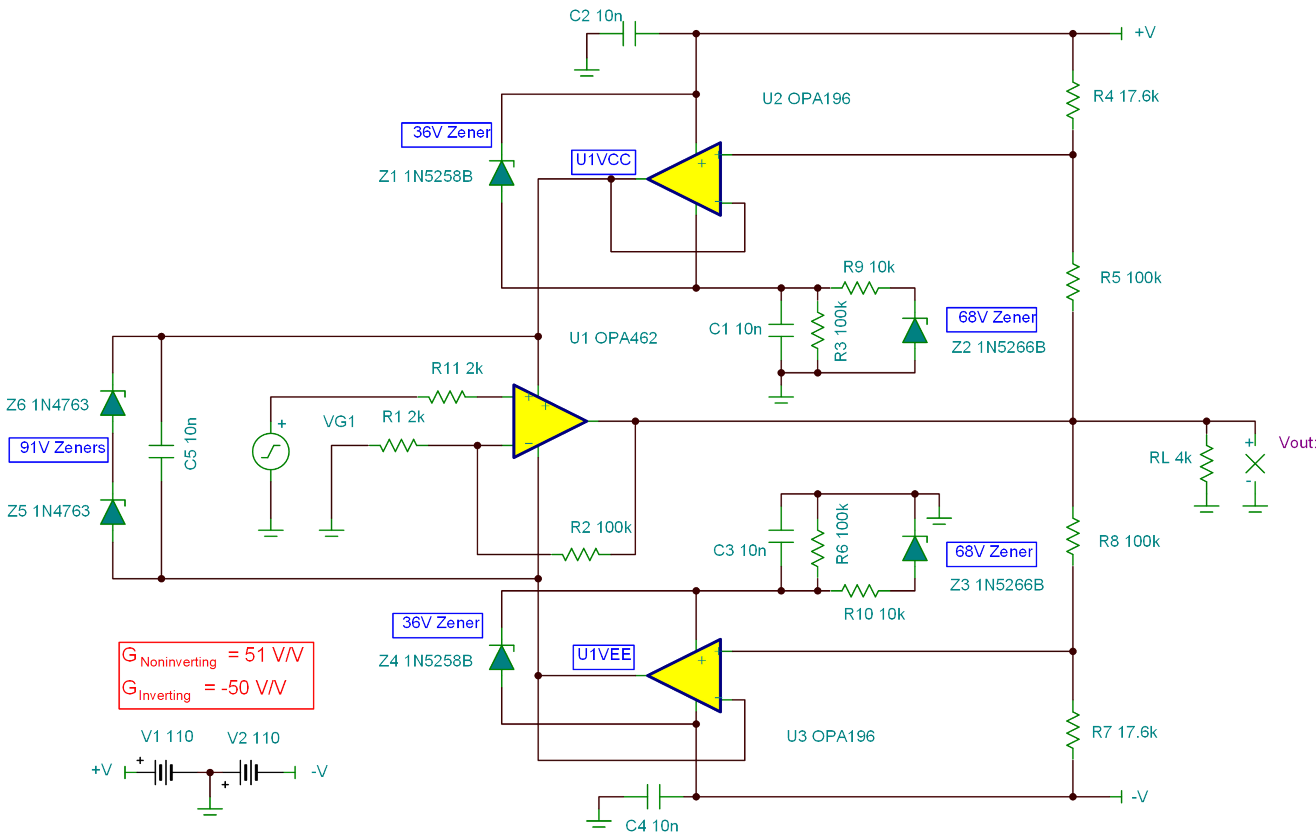

Figure A-8. Lower Voltage, Lower Cost Three Op-amp Solution

A.9.2 Conventions

Channel 1 is the U1 output.

Channel 2 is the U1 noninverting input.

Channel 3 is the U1VCC rail.

Channel 4 is the U1VEE rail.

A.9.3 Results

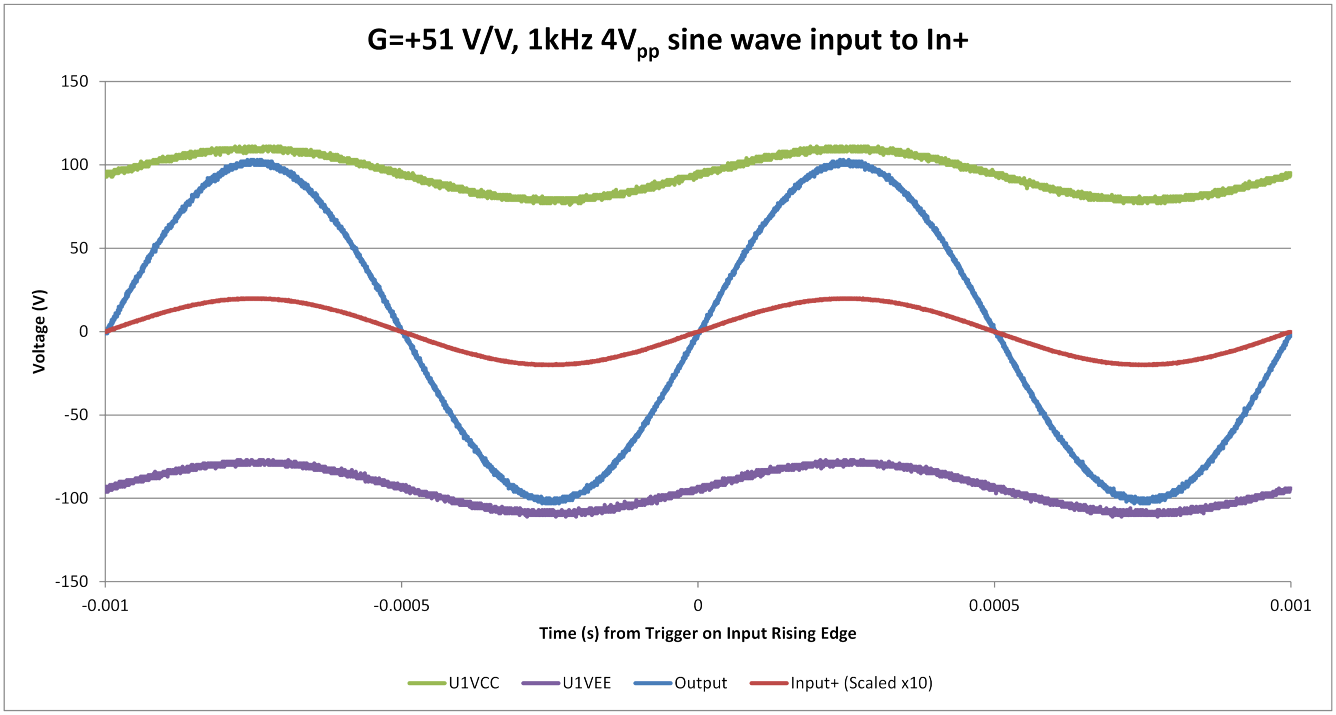

Figure A-9. Noninverting Configuration, G = +51 V/V, 1-kHz Sine Wave (Output 206 V_{pp})

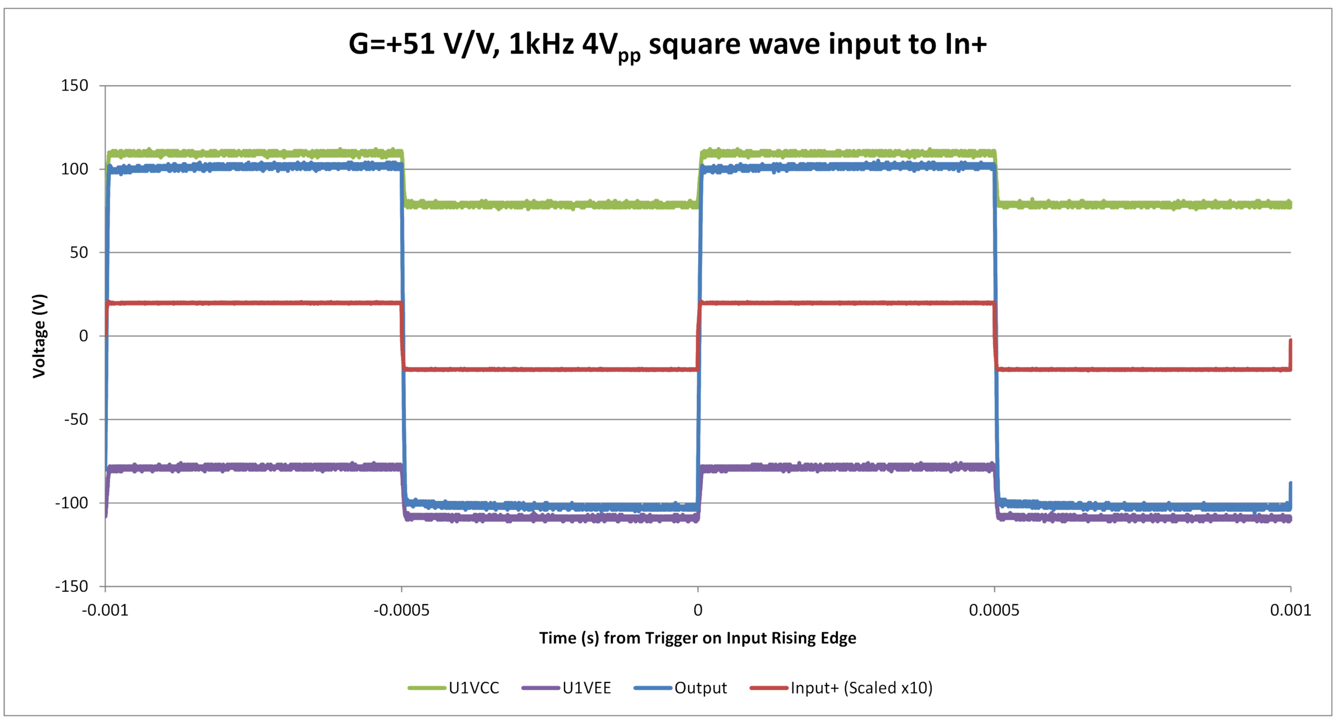

Figure A-10. Noninverting Configuration, G = +51 V/V, 1-kHz Square Wave (Output 211 V_{pp})

Figure A-11 and Figure A-12 show the falling and rising edges of the above square wave waveform but at a higher zoom level. Note that the actual values of Channels 1, 3, and 4 are 10 × greater than the image implies, due to the attenuation settings of the scope probes.

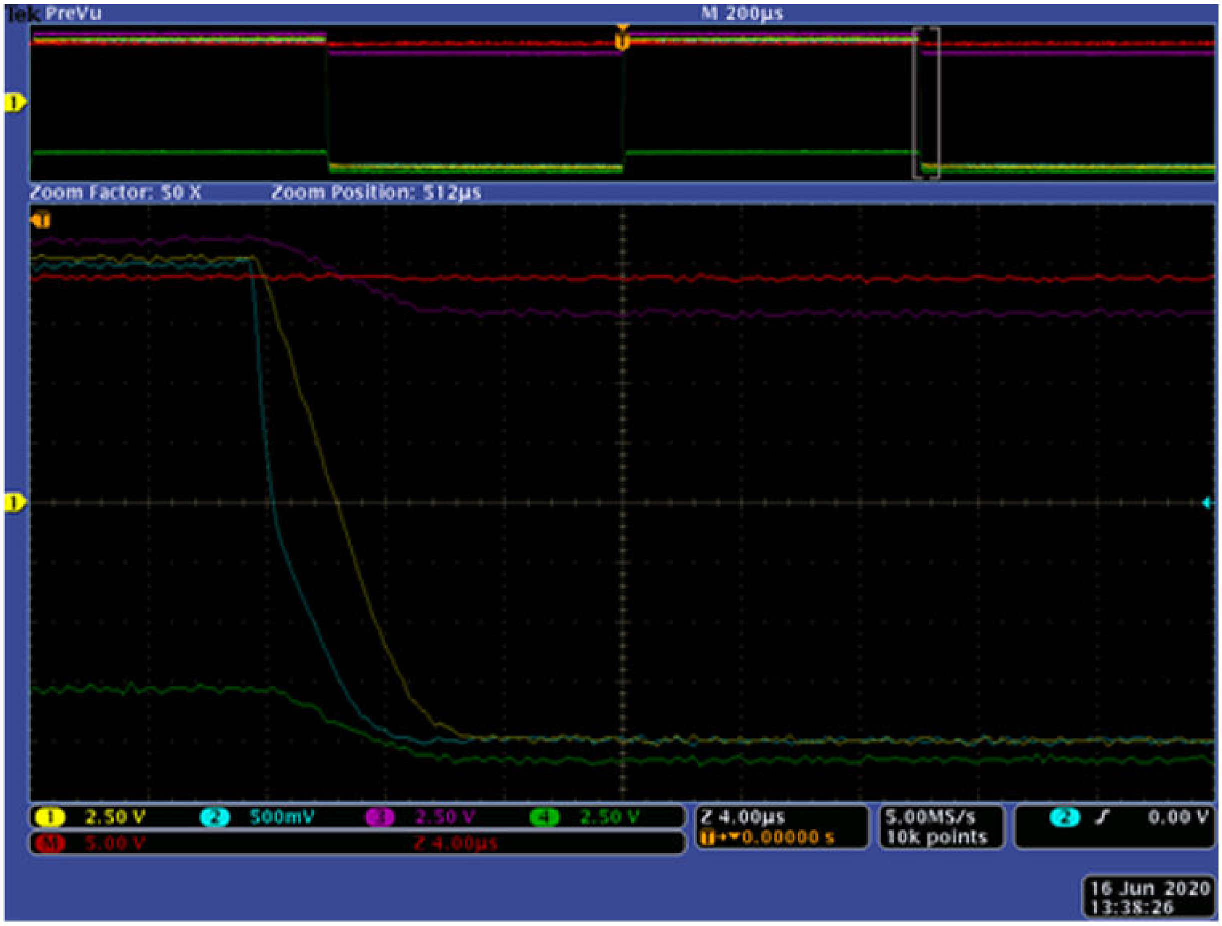

Figure A-11. Noninverting Configuration, G = +51 V/V, 1-kHz Square Wave (4 V_{pp}), Zoom on Falling Edge

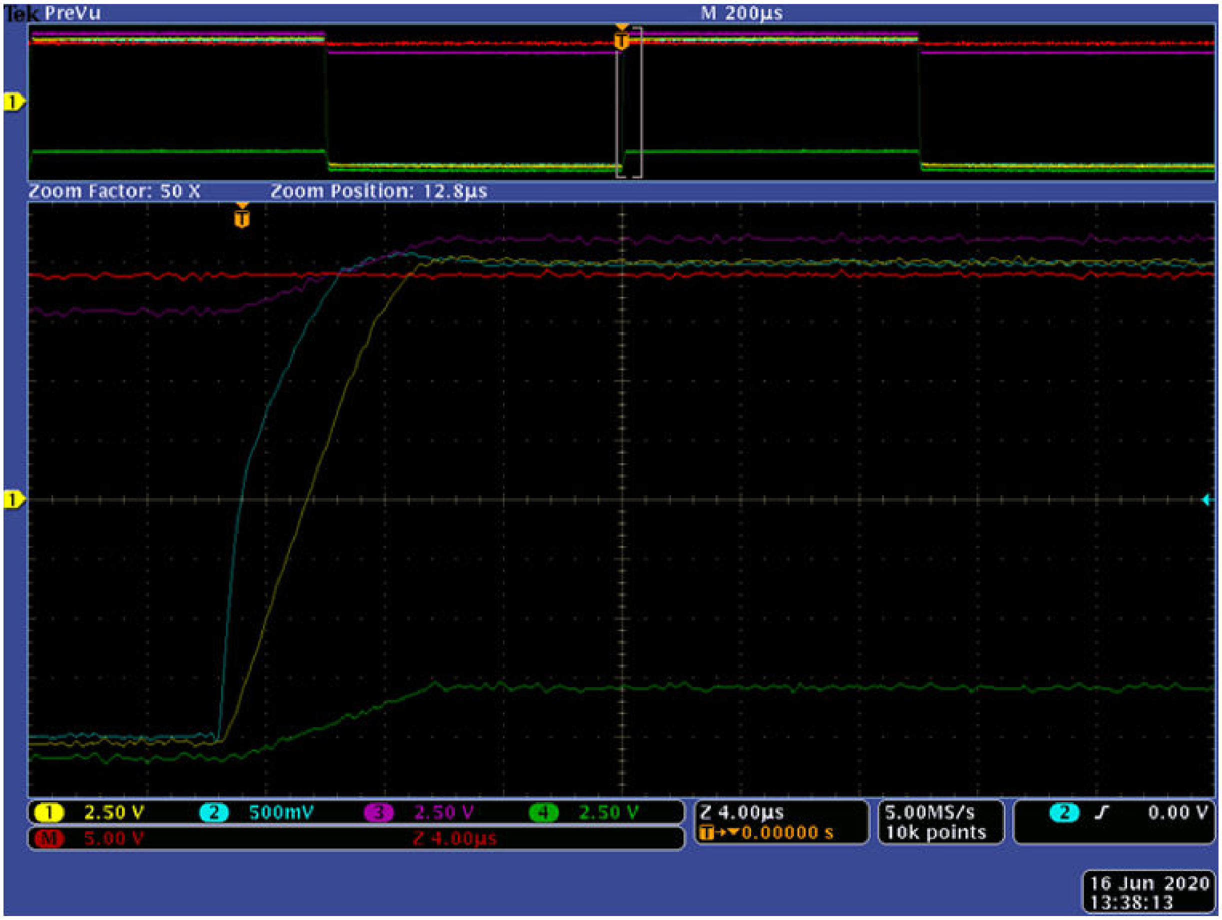

Figure A-12. Noninverting Configuration G = +51 V/V, 1-kHz Square Wave (4 V_{pp}), Zoom on Rising Edge

A.10 Circuit 3: OPA462 300 V_{pp} Output Solution With Discrete Transistor Supply-Rail Drivers

A.10.1 Schematic

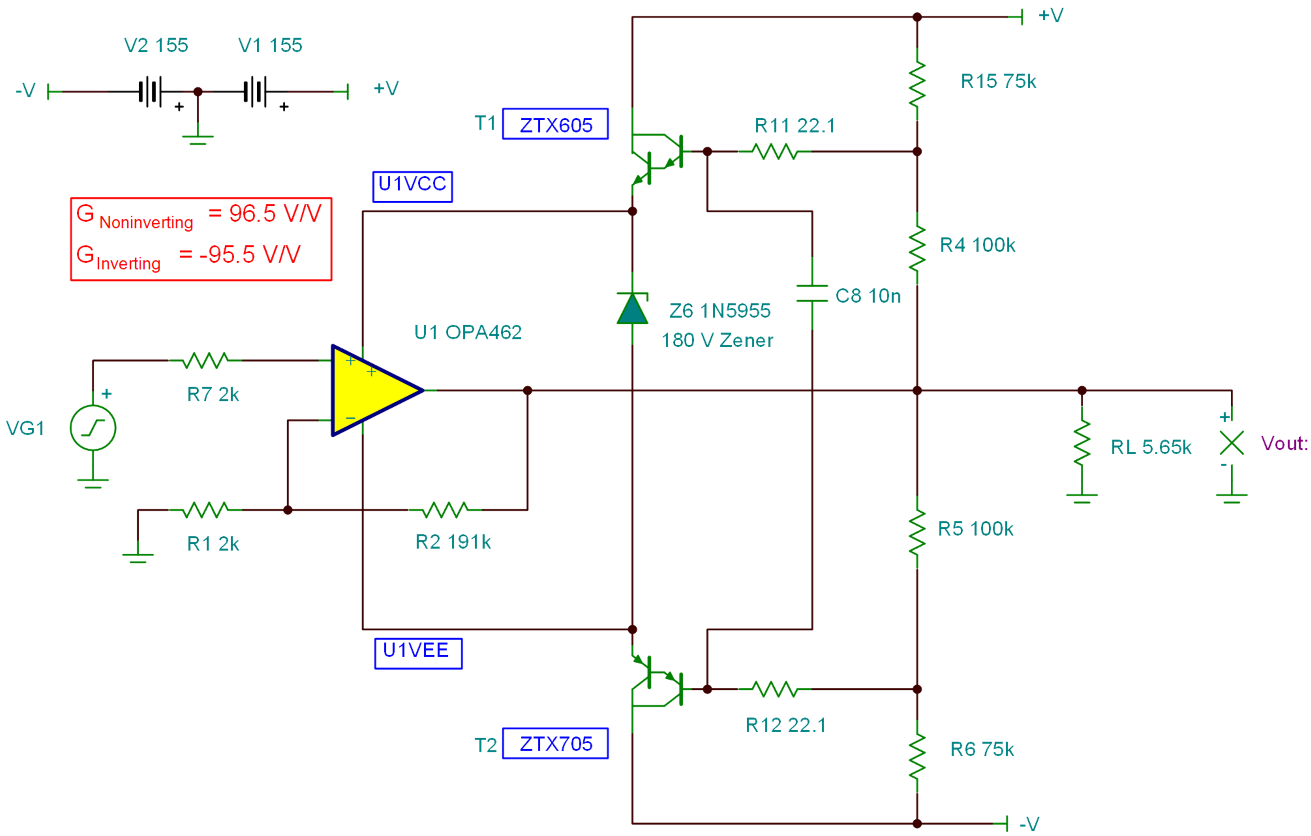

Figure A-13. OPA462 300 V_{pp} Output Solution With Discrete Transistor Supply-Rail Drivers

A.10.2 Conventions

Channel 1 is the U1 output.

Channel 2 is the U1 noninverting input.

Channel 3 is the U1VCC rail.

Channel 4 is the U1VEE rail.

A.10.3 Results

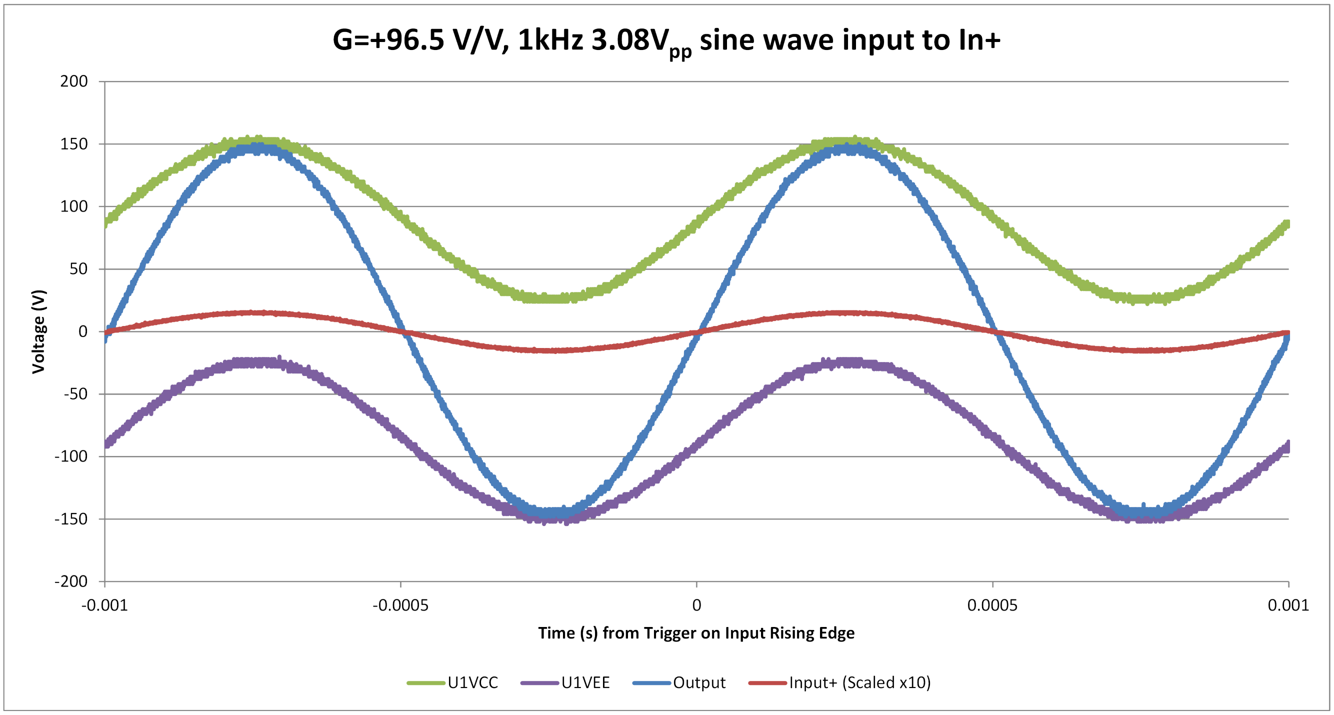

Figure A-14. Noninverting Configuration, G = +96.5 V/V,1 kHz Sine Wave (Output 298 V_{pp})

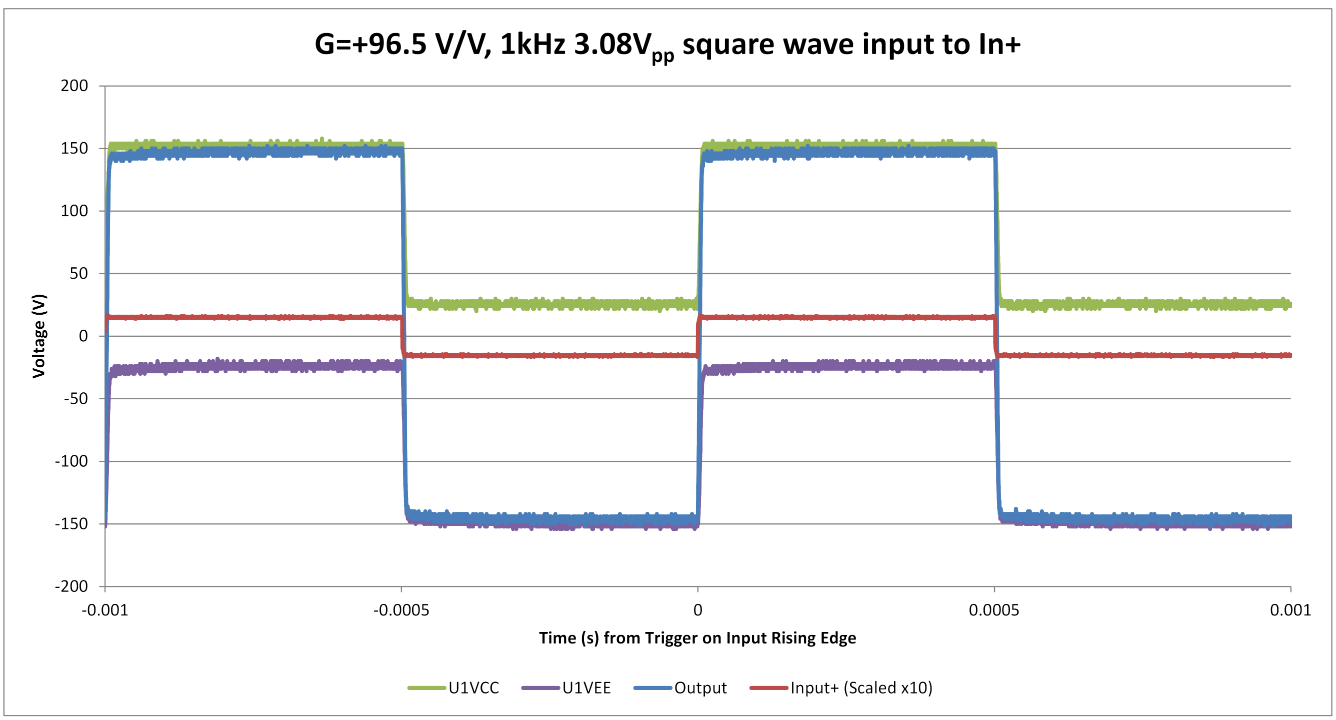

Figure A-15. Noninverting Configuration, G = +96.5 V/V, 1-kHz Square Wave (Output 304 V_{pp})

Figure A-16 and Figure A-17 show the falling and rising edges of the above square waveform but at a higher zoom level. Note that the actual values of Channels 1, 3, and 4 are 10 × greater than the image implies, due to the attenuation settings of the scope probes.

Figure A-16. Noninverting Configuration, G = +96.5 V/V, 1-kHz Square Wave (3.08 V_{pp}), Zoom on Falling Edge

Figure A-17. Noninverting Configuration, G = +96.5 V/V, 1-kHz Square Wave (3.08 V_{pp}), Zoom on Rising Edge