Application Report
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How to Use the Smart Analog Combo in MSP430™ MCUs

Darren Lu *MSP430 Applications*

ABSTRACT

Operational amplifiers (Op Amps or OAs) are used extensively in sensing and measurement applications. MSP430™ microcontrollers (MCUs) provide full signal chain implementation with the integrated Smart Analog Combo (SAC) to replace external Op Amps. The Smart Analog Combo is a configurable analog peripheral that includes a high-performance low-power Op Amp, a programmable gain amplifier (PGA) with gain up to 33, and a 12-bit digital-to-analog converter (DAC). This application report describes how to use the Smart Analog Combo module in MSP430 MCUs. Smart Analog Combo concept, operation modes, internal connection, ROM-based driver library, and design consideration are described. This application report also describes Smart Analog Combo use cases and the benefits of using the module in smoke detector and current loop applications.

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1 Introduction

Various sensors convert physical quantities in the real world into electrical signals. The sensor's output signal is usually with small amplitude and noise, so that it must be amplified and filtered. The operational amplifier is a vital component for signal conditioning like amplification and filtering. After signal conditioning, an analog-to-digital converter (ADC) is used to convert the analog signal into a digital signal for the processor or controller to analyze. MSP430 MCUs provide signal chain elements with highly integrated analog peripherals for sensing and measurement applications. Within the MSP430FR23xx family of MCUs, the integrated Smart Analog Combo is a key differentiated analog peripheral that includes a high-performance low-power operational amplifier, a PGA with gain up to 33, and a 12-bit digital-to-analog converter. The Smart Analog Combo provides flexible analog configuration on one chip that saves BOM cost and PCB size. This application report discusses how to use Smart Analog Combo in MSP430 MCUs. It introduces the theory of operation, operation modes, internal connection, ROM-based driver library, design considerations, and application use cases.

1.1 Smart Analog Combo Concept

The Smart Analog Combo module includes one programmable gain amplifier (PGA) and one 12-bit digital-to-analog converter (DAC). The module can be used for signal conditioning in input path and waveform generation in output path. There are three different configuration levels for Smart Analog Combo: SAC-L1, SAC-L2, and SAC-L3.

- SAC-L1 is the minimum feature set and integrates only the operational amplifier.
- SAC-L2 includes the operational amplifier and a feedback resistance ladder to form a PGA with gain up to 33.
- SAC-L3 is the maximum feature set that integrates the SAC-L2 PGA and a 12-bit DAC.

Different MSP430 MCUs have different Smart Analog Combo configuration levels. For example, MSP430FR2311 integrates one SAC-L1 module, and MSP430FR2355 integrates four SAC-L3 modules. For the Smart Analog Combo configuration level and quantity on a specific MCU, see the device-specific data sheet.

Figure 1 shows the block diagram of SAC-L3 module. The integrated amplifier supports rail-to-rail input and rail-to-rail output. The two internal multiplexers support multiple input selections for the operational amplifier (OA). The op-amp power mode (OAPM) control bit selects the OA power mode. In high-power mode, the OA provides higher gain bandwidth and slew rate. If lower power consumption is more critical in the application, select the OA low-power mode by setting the OAPM bit to 1. The feedback resistance ladder connects the OA output with the negative input as the feedback routing. With the feedback routing, the OA supports both inverting PGA mode and noninverting PGA mode. A 12-bit DAC is also integrated in the SAC-L3 module. The DAC can be used to generate a bias voltage to the OA or can work with OA to drive a waveform output on the pad.

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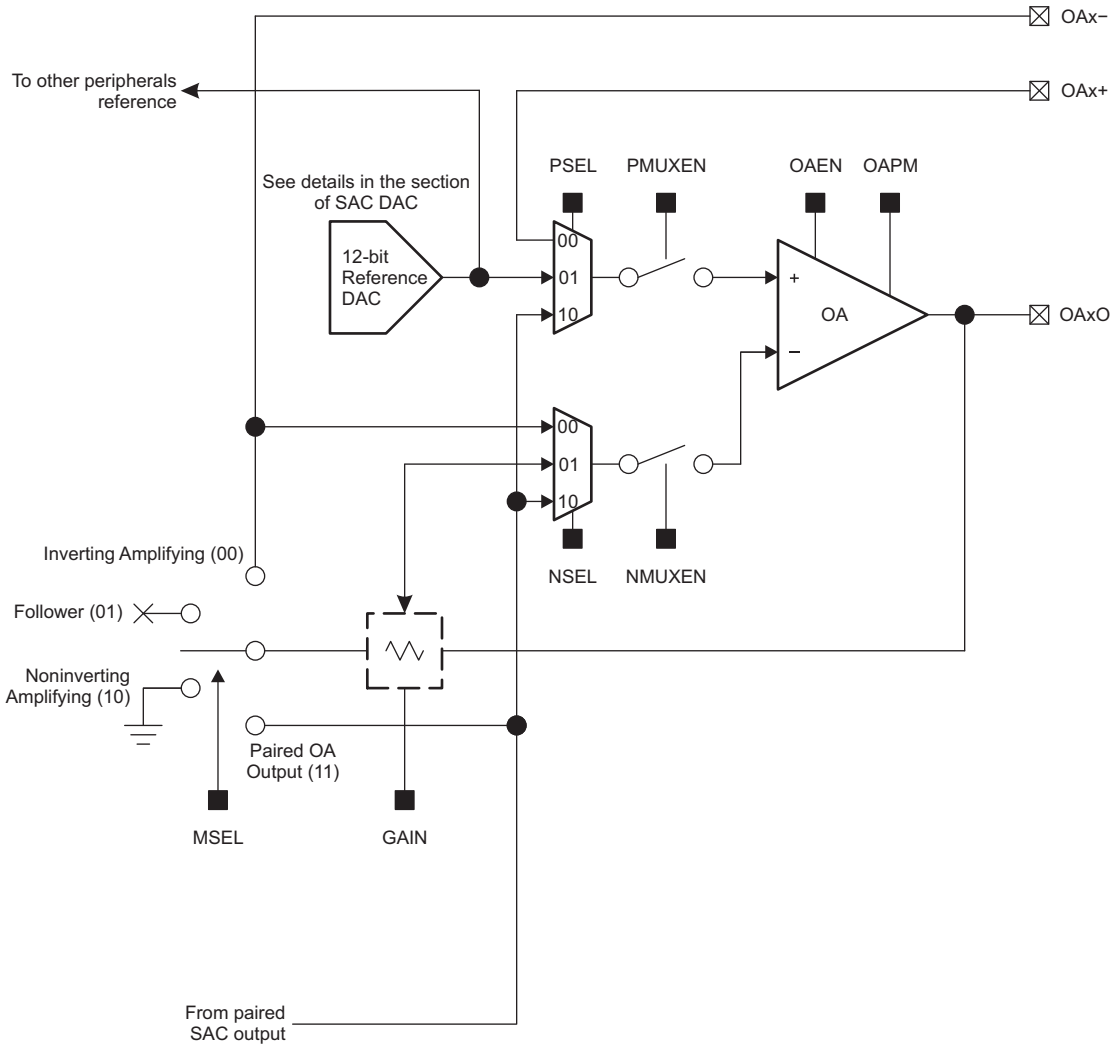

Figure 1. Smart Analog Combo Block Diagram

1.2 Single-Supply Amplifier Design Consideration

Because the Smart Analog Combo (SAC) is one of the analog peripherals in the MSP430 MCU, the SAC is supplied by the power pin on the MSP430 MCU. The integrated OA is a single-supply design with a wide supply voltage range from 2 V to 3.6 V. The OA inputs are referenced to ground. A dual-supply OA circuit design is straightforward, because the OA inputs and output are referenced to the normally grounded center of the supplies. The single-supply OA design is a little more complicated than a dual-supply OA as some form of biasing is usually required for single-supply OA. The OA input and output voltages must be within its two power rails. The SAC does not support negative voltage input or output. When the SAC is in inverting amplifier mode, biasing on the positive input is essential to avoid clipping distortion. Figure 2 shows the typical circuit for single-supply amplifier working in inverting mode. V_{REF} and the resistor divider are used to generate bias voltage, and the SAC DAC12 with built-in reference can replace the external reference and resistor divider. With the SAC feedback resistance ladder, the circuit in Figure 2 can be implemented using one SAC without any external components.

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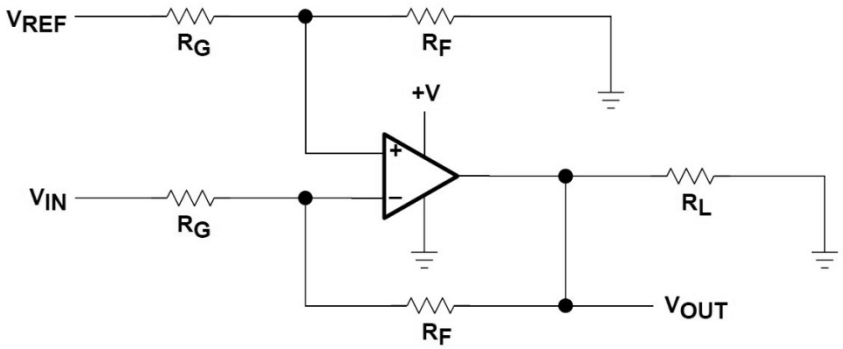

Figure 2. Single-Supply Inverting Amplifier

When the SAC is in noninverting amplifier mode, if the DC component of input signal is small, it is acceptable to amplify both the DC component and AC component. If the input signal contains relatively high DC component while its AC component is small, amplifying the small AC component need high gain but amplifying the DC component with high gain leads to amplifier distortion. Adding biasing on the negative voltage input can address this issue by reducing the common-mode input voltage. Figure 3 shows the typical circuit for single-supply amplifier working in noninverting mode. Similar to the inverting amplifier circuit, the noninverting amplifier can also be implemented using the SAC without external components. The difference is that two SAC modules are needed, because the DAC can be connected only to the positive input of the OA, and the second SAC works in DAC mode to generate the bias voltage to the negative input of the OA. For more details and design considerations for single-supply amplifiers, see Single-Supply Op Amp Design Techniques.

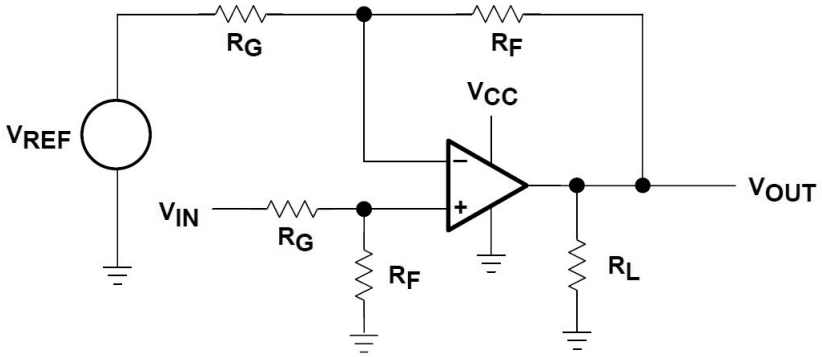

Figure 3. Single-Supply Noninverting Amplifier

1.3 Smart Analog Combo Driver Library

All MSP430 FRAM MCUs support a driver library (DriverLib) to help users accelerate firmware development. The MSP430 driver library is a high-level easy-to-use abstracted programming interface, which keeps users above the bits and bytes of MSP430 hardware registers by providing simple function calls for every peripheral. This helps users spend less time learning and more time innovating with MSP430 MCUs. Some MSP430 MCUs like MSP430FR2355 include a complete peripheral driver library fully integrated into the ROM memory. Developers can leverage the ROM-based driver library for more benefits including single-cycle ROM execution at higher CPU clock frequency and saving FRAM space for additional application code.

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More than twenty API functions are available for the SAC module. These API functions are provided to initialize the SAC, enable the SAC, disable the SAC, set the SAC operation mode, configure the DAC, select the DAC reference, select the power mode, and so on. Each API function is fully tested and documented. The FRAM-based driver library is completely open source, which can help developers understand what is happening beneath the abstraction layer. Developers can access the ROM-based APIs by adding the driver library header file to their projects and linking to the attribute library. This application report describes how to use SAC with driver library. For more information on SAC API functions, see the *MSP430 DriverLib for MSP430FR2xx_4xx Devices User's Guide*.

2 Smart Analog Combo Operation Modes

2.1 General Purpose Mode

Figure 4 shows the configuration of SAC general-purpose mode. In this mode, OAx+ and OAx- are dedicated signal inputs. As the red highlighted part in Figure 4 shows, the internal DAC and feedback resistance ladder are not used. There is no limitation when using the SAC in general-purpose mode, it is the same as using external single-supply operational amplifier. You can use the SAC and external component to compose kinds of different circuits such as an inverting amplifier, noninverting amplifier, filter, and so on. Biasing and a feedback resistor usually must be added. External components and connections determine the circuit type. It is convenient to migrate from an external amplifier circuit to the integrated SAC in general-purpose mode. Compared to an external amplifier, the SAC can have the same circuit type while saving BOM cost and PCB size. When the SAC is not in use, it can be disabled by the control register in the MSP430 MCU to save power. SAC-L1 supports only general-purpose mode and does not include the DAC or the feedback resistance ladder.

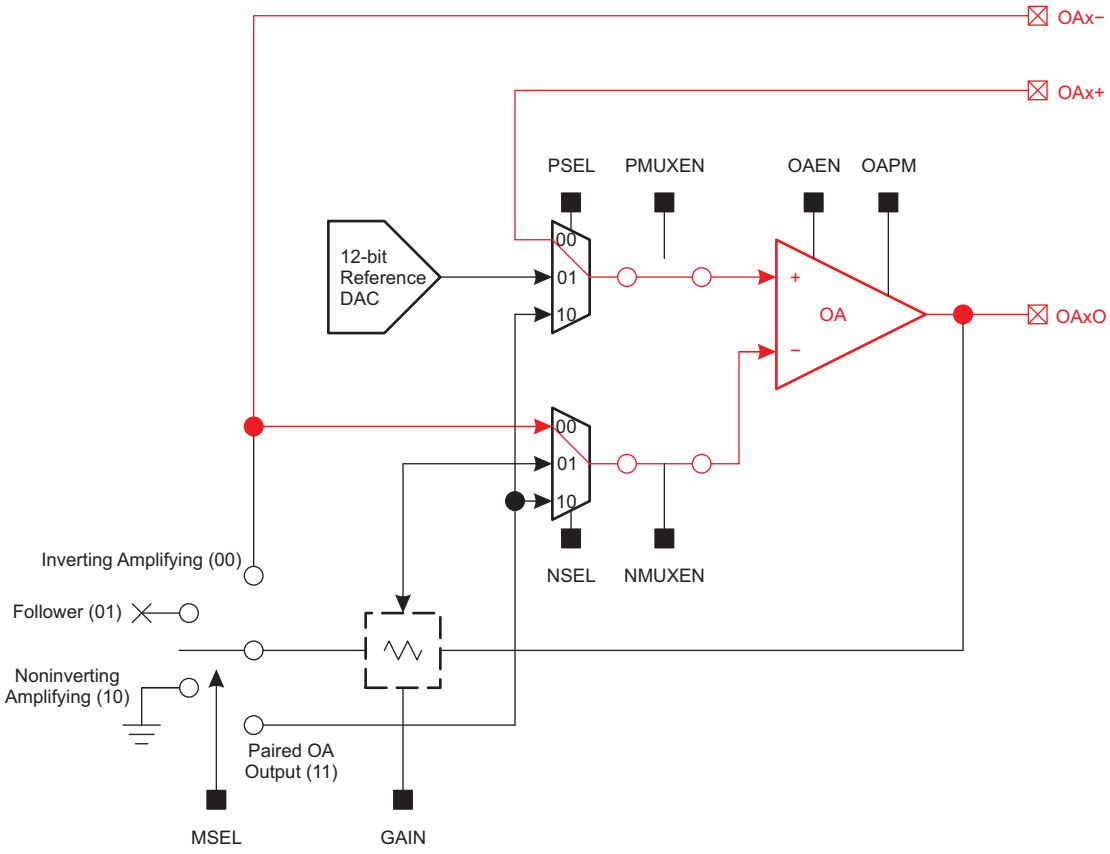

Figure 4. Smart Analog Combo General-Purpose Mode

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To configure the SAC for general-purpose mode, the SACEN, OAEN, PMUXEN, and NMUXEN bits must be set in the SAC OA control register SACxOA. The PSEL and NSEL bits are also in SACxOA register, and they are configured to select external pins as the OA inputs by default. The OAPM bit is used to select high-speed or low-speed mode. The high-speed mode enables higher gain bandwidth and slew rate at the cost of higher power consumption. Example 1 shows one code sequence of configuring SAC into general-purpose mode with driver library API functions. The pin function must be selected as SAC function before SAC module configuration, although this example code does not include the pin function setting. Different MSP430 MCU has different pin definitions (see the data sheet for details).

Example 1. Code Example for Smart Analog Combo General-Purpose Mode

```
//Select external source for both positive and negative inputs
SAC_OA_init(SAC0_BASE, SAC_OA_POSITIVE_INPUT_SOURCE_EXTERNAL,
            SAC_OA_NEGATIVE_INPUT_SOURCE_EXTERNAL);
//Select low speed and low power mode
SAC_OA_selectPowerMode(SAC0_BASE, SAC_OA_POWER_MODE_LOW_SPEED_LOW_POWER);
// Enable OA
SAC_OA_enable(SAC0_BASE);
// Enable SAC
SAC_enable(SAC0_BASE);
```


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2.2 Buffer Mode

Figure 5 shows the SAC buffer mode. The buffer is unity gain, and it is also called a voltage follower. A voltage follower is often used to solve impedance matching problems, improve output drive strength, and isolate high-precision circuits from high-power circuits.

As the red highlighted part in Figure 5 shows, the signal input is from the positive port, the external pad, or the OA in SAC buffer mode. The output of the OA is isolated from the R-ladder, and PGA MSEL is set to floating status. The OA can output to an external pin or internally to a paired OA. To configure the SAC into buffer mode, the NSEL bits must select PGA source as negative input (NSEL = 01b), and MSEL bits must select buffer mode (MSEL = 01b). Example 2 shows one code sequence of configuring the SAC into buffer mode with driver library API functions.

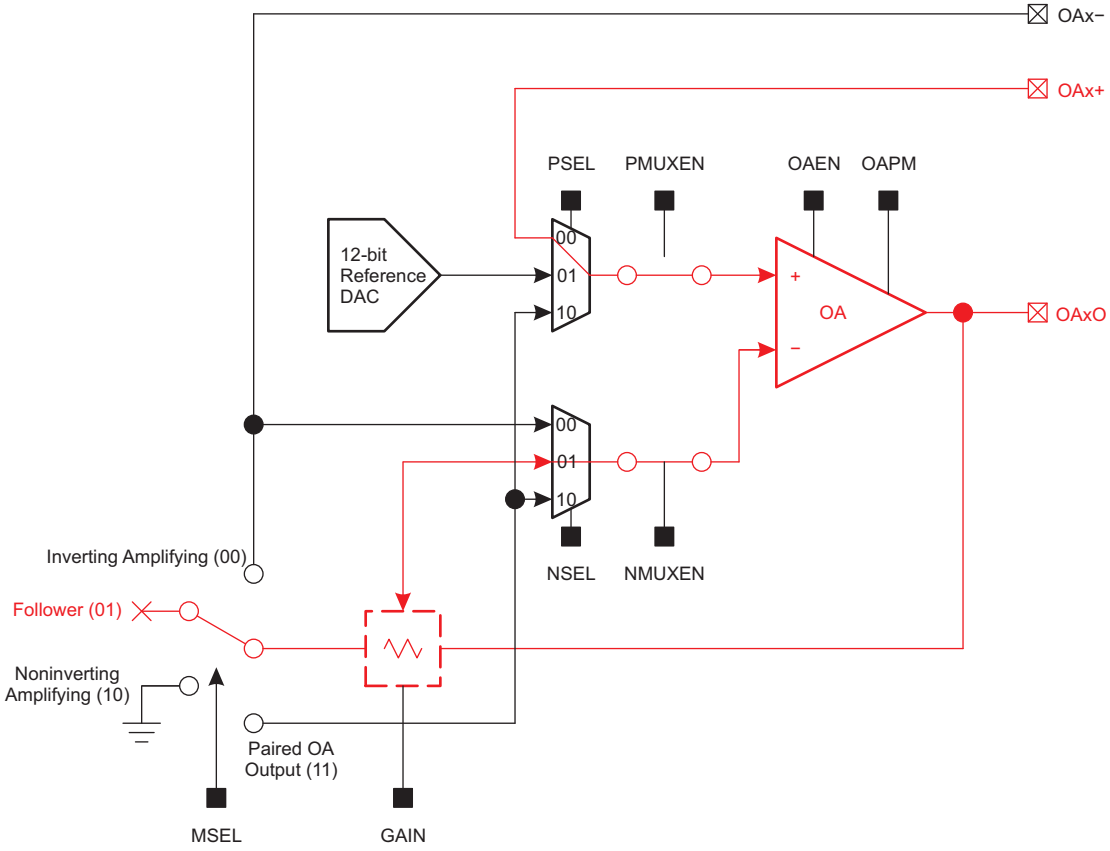

Figure 5. Smart Analog Combo Buffer Mode

Example 2. Code Example for Smart Analog Combo Buffer Mode

```
//Select external source for positive input and PGA source for negative input
SAC_OA_init(SAC0_BASE, SAC_OA_POSITIVE_INPUT_SOURCE_EXTERNAL,
            SAC_OA_NEGATIVE_INPUT_SOURCE_PGA);
//Select Buffer Mode
SAC_PGA_setMode(SAC0_BASE, SAC_PGA_MODE_BUFFER);
//Enable OA
SAC_OA_enable(SAC0_BASE);
//Enable SAC
SAC_enable(SAC0_BASE);
```


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2.3 Noninverting PGA Mode

Figure 6 shows the SAC noninverting PGA mode. In this mode, signal can be amplified without inverting. This is useful for single-supply amplifier where negative voltage is not allowed. External feedback is not necessary that the internal configurable resistor ladder determines the amplifier gain. There are 8 different gain settings from 1x to 33x.

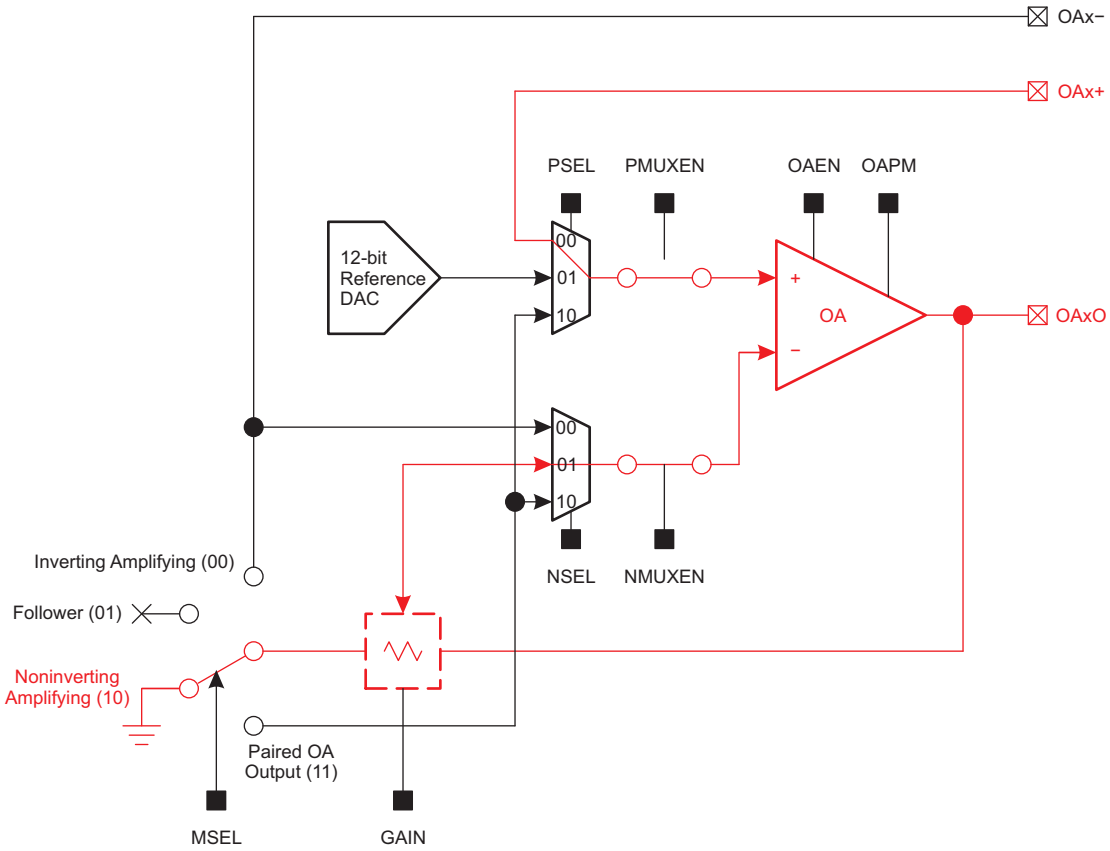

Figure 6. Smart Analog Combo Noninverting PGA Mode

As the red highlighted part in Figure 6 shows, the signal input can be selected from the positive port OAx+ or a paired OA. The OA negative port must select PGA input (NSEL = 01b), and the PGA MSEL is set to ground (MSEL = 10b).SAC gain is configured by GAIN bits in SACxPGA control register. Example 3 shows one code sequence of configuring SAC into noninverting PGA mode with driver library API functions.

Example 3. Code Example for Smart Analog Combo Noninverting PGA Mode

```
//Select external source for positive input and PGA source for negative input
SAC_OA_init(SAC0_BASE, SAC_OA_POSITIVE_INPUT_SOURCE_EXTERNAL,
            SAC_OA_NEGATIVE_INPUT_SOURCE_PGA);
//Select Non-inverting PGA Mode
SAC_PGA_setMode(SAC0_BASE, SAC_PGA_MODE_NONINVERTING);
//Set Non-inverting PGA gain = 3
SAC_PGA_setGain(SAC0_BASE, SAC_PGA_GAIN_BIT1);
//Enable OA
SAC_OA_enable(SAC0_BASE);
//Enable SAC
SAC_enable(SAC0_BASE);
```


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2.4 Inverting PGA Mode

Figure 7 shows the SAC Inverting PGA mode. In this mode, signal can be amplified with inverting. As negative voltage is not allowed in SAC usage, biasing is must have for SAC inverting PGA mode. Bias voltage can be generated by external circuit or internal 12-bit DAC. The red highlighted part in Figure 7 shows the use case that using internal DAC to generate bias voltage at OA positive input. Usually bias voltage is half of the power supply voltage. The signal input is from external pin OAx- or internal paired OA.

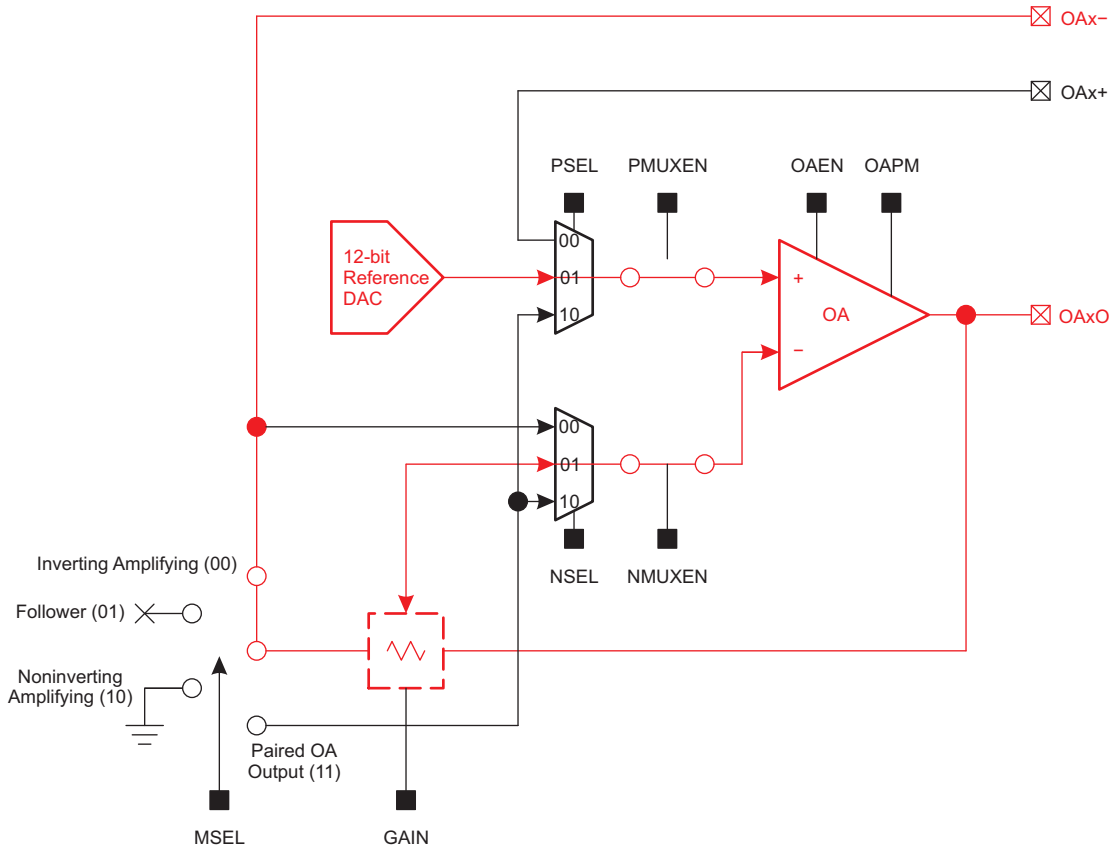

Figure 7. Smart Analog Combo Inverting PGA Mode

To configure SAC into inverting PGA mode, The PGA MSEL selects OAx- (MSEL = 00b) or a paired OA (MSEL = 11b) as the source, and the OA negative port must select PGA input (NSEL = 01b). The OA positive port can select from the external pin OAx+ or the 12-bit DAC. SAC gain is configured by GAIN bits in SACxPGA control register. Example 4 shows one code sequence of configuring SAC into inverting PGA mode with driver library API functions.

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Example 4. Code Example for Smart Analog Combo Inverting PGA Mode

```
//Select VCC as DAC reference voltage
SAC_DAC_selectRefVoltage(SAC0_BASE, SAC_DAC_PRIMARY_REFERENCE);
//Select load trigger for DAC latch. DAC latch loads when DACDAT written
SAC_DAC_selectLoad(SAC0_BASE, SAC_DAC_LOAD_DACDAT_WRITTEN);
//Set 1/2 VCC as DAC output voltage, Vout = Vref * DACDAT / 4096
SAC_DAC_setData(SAC0_BASE, 2048);
//Enable DAC
SAC_DAC_enable(SAC0_BASE);
//Select internal DAC for positive input and PGA source for negative input
SAC_OA_init(SAC0_BASE, SAC_OA_POSITIVE_INPUT_SOURCE_DAC,
            SAC_OA_NEGATIVE_INPUT_SOURCE_PGA);
//Select Inverting PGA Mode
SAC_PGA_setMode(SAC0_BASE, SAC_PGA_MODE_INVERTING);
//Set Inverting PGA gain = 2
SAC_PGA_setGain(SAC0_BASE, SAC_PGA_GAIN_BIT1);
//Enable OA
SAC_OA_enable(SAC0_BASE);
//Enable SAC
SAC_enable(SAC0_BASE);
```


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2.5 DAC Mode

The SAC-L3 includes a 12-bit DAC. The DAC can be used as the reference voltage and also can work with the OA and PGA to drive the output pad directly. When using DAC to generate signal and drive other circuit, OA must be configured into buffer mode to improve the drive strength. The red highlighted part in Figure 8 shows the SAC DAC mode, in this mode, the 12-bit DAC and built-in OA must be enabled together, and PGA MSEL is set to floating status.

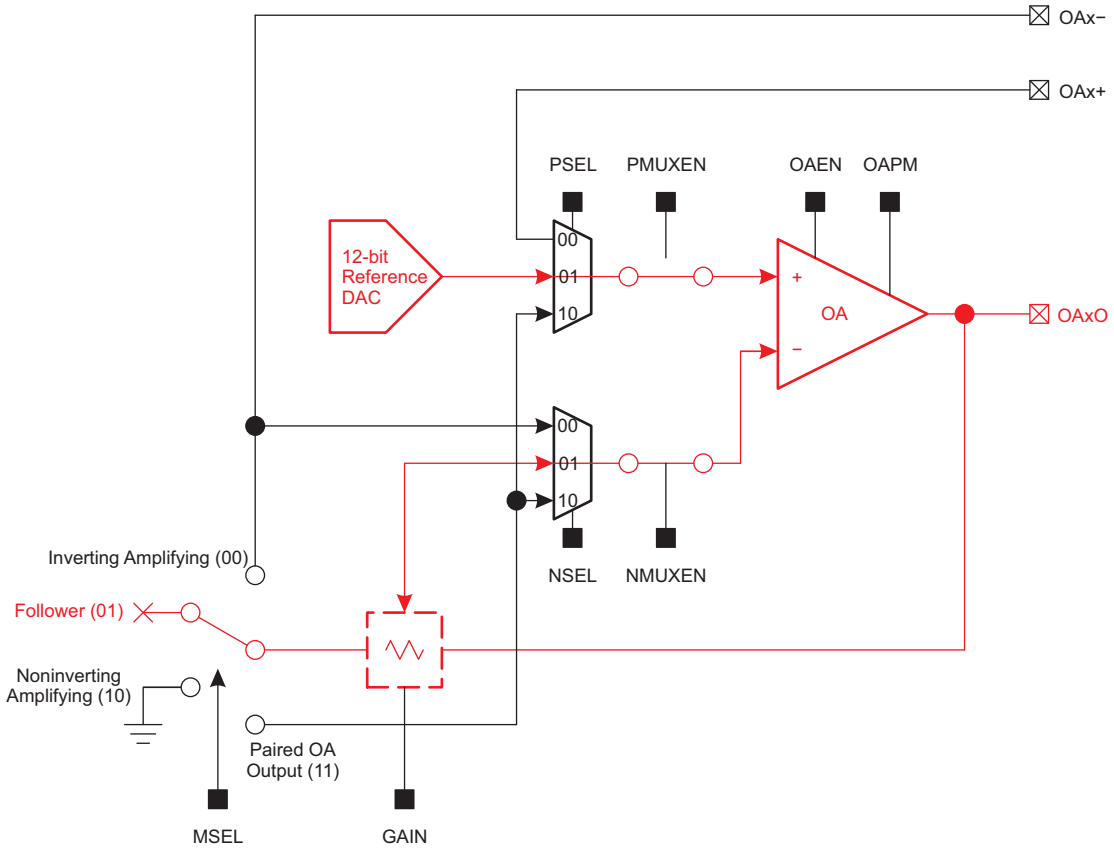

Figure 8. Smart Analog Combo DAC Mode

Example 5 shows one code sequence of configuring the SAC into DAC mode with driver library API functions. In this code, the internal shared reference is selected as the DAC reference and the DAC always loads data from DACDAT at the positive edge of timer output TB2.1. The DAC module can generate an interrupt when DACIE is set, a set DACIFG bit indicate that the DAC is ready for new data. There are two device-specific references selected by DACSREF bits. The MSP430FR2355 MCU supports an internal shared reference and V_{CC} as the DAC reference. The trigger signal for the DAC loading data is also device-specific, this code only shows one configuration and users change the configuration by changing API parameters. Example 5 shows only the configuration code for the SAC module. To make SAC work in DAC mode, users should also take care of other related things like internal shared reference setting, Timer_B2 setting, and interrupt service routine.

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Example 5. Code Example for Smart Analog Combo DAC Mode

```
//Select internal shared reference as DAC reference voltage
SAC_DAC_selectRefVoltage(SAC0_BASE, SAC_DAC_SECONDARY_REFERENCE);
//Select the load trigger for DAC data latch
//DAC always loads data from DACDAT at the positive edge of Timer output TB2.1
SAC_DAC_selectLoad(SAC0_BASE, SAC_DAC_LOAD_DEVICE_SPECIFIC_0);
//Enable DAC Interrupt
SAC_DAC_interruptEnable(SAC0_BASE);
//Write data to DAC Data Register SACxDAT
//DAC_data is an unsigned int type variable defined by user
SAC_DAC_setData(SAC0_BASE, DAC_data);
//Enable DAC
SAC_DAC_enable(SAC0_BASE);
//Select internal DAC for positive input and PGA source for negative input
SAC_OA_init(SAC0_BASE, SAC_OA_POSITIVE_INPUT_SOURCE_DAC,
            SAC_OA_NEGATIVE_INPUT_SOURCE_PGA);
//Select Buffer Mode
SAC_PGA_setMode(SAC0_BASE, SAC_PGA_MODE_BUFFER);
//Enable OA
SAC_OA_enable(SAC0_BASE);
//Enable SAC
SAC_enable(SAC0_BASE);
```


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3 Smart Analog Combo Interconnection Configuration

3.1 Smart Analog Combo Cascading

The analog circuit is usually complicated which requires different functions like amplification, filtering, buffering combined in one circuit. The multiple requirements cannot be achieved by a single amplifier so that amplifier cascading is widely used. One typical use case for two-stage cascaded amplifiers is that the first-stage amplifier set as high gain amplifier and the second-stage amplifier set as buffer. By this way, both high gain and high output drive strength can be achieved. MSP430FR2355 integrates four SAC modules (SAC0, SAC1, SAC2, and SAC3) with flexible interconnection. SAC0 is paired with SAC2, and SAC1 is paired with SAC3. The SAC0 output is connected to the SAC2 positive and negative inputs. The SAC2 output is connected to the SAC0 positive and negative inputs. SAC1 and SAC3 have interconnections similar to the interconnections of SAC0 and SAC2. With the internal connections of the MSP430 MCU, the cascaded SAC modules can be configured multiple operation modes, and board layout is also simplified.

Figure 9 shows one example of two cascaded noninverting amplifiers. The noninverting output of the first OA is internally connected to the noninverting positive input of the second OA by selecting the paired OA output as the positive input (PSEL = 10b).

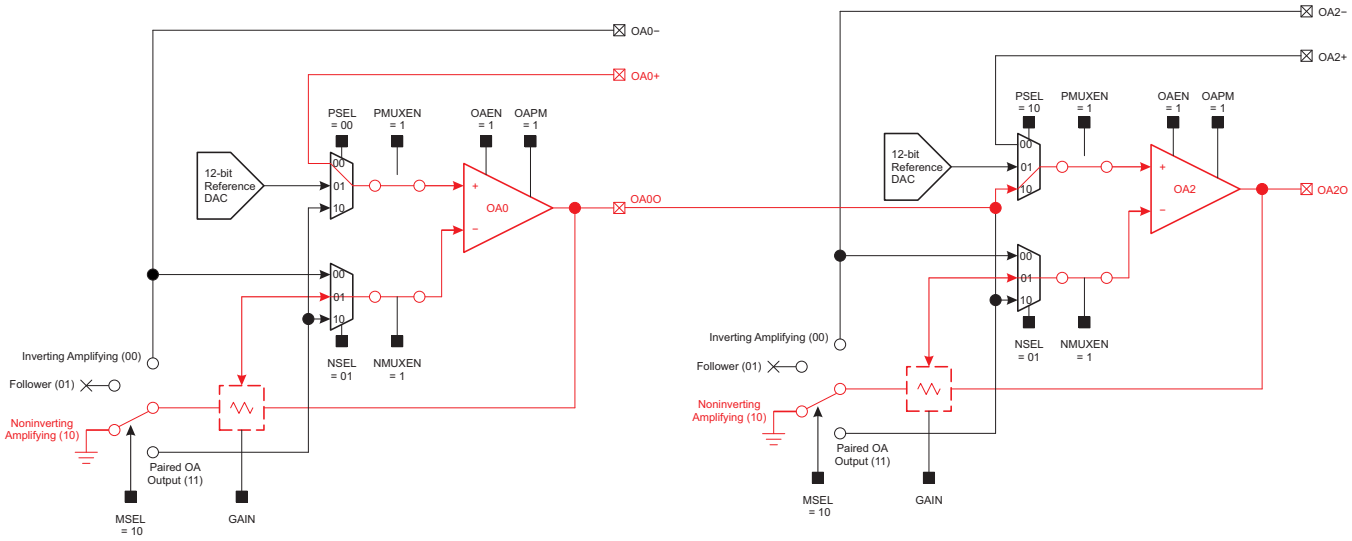

Figure 9. Smart Analog Combo Cascading Example 1

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Figure 10 shows the oscilloscope waveform of SAC cascading example 1. Channel 1 is the input signal of first stage SAC. Channel 2 is the output signal of first stage SAC. Channel 3 is the output of second stage SAC. As Figure 10 shows, the input signal is amplified twice without inverting. The first stage amplifier amplifies the signal by 3 times and the second amplifier amplifies the signal by 2 times. The total gain is 6.

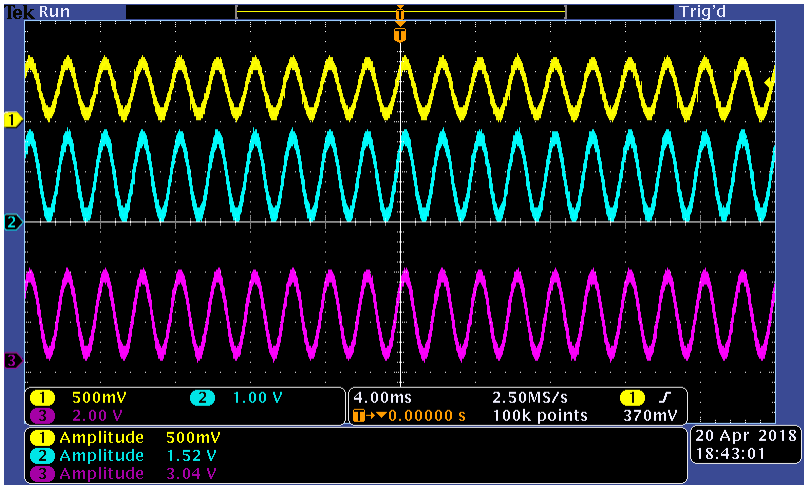

Figure 10. Smart Analog Combo Cascading Waveform 1

Figure 11 shows another example of two cascaded inverting amplifiers. The output of the first inverting OA is internally connected to the resistor ladder of the second inverting OA as the negative input. This configuration can be achieved by setting SAC PGA mode into cascade OA inverting mode (MSEL = 11b).

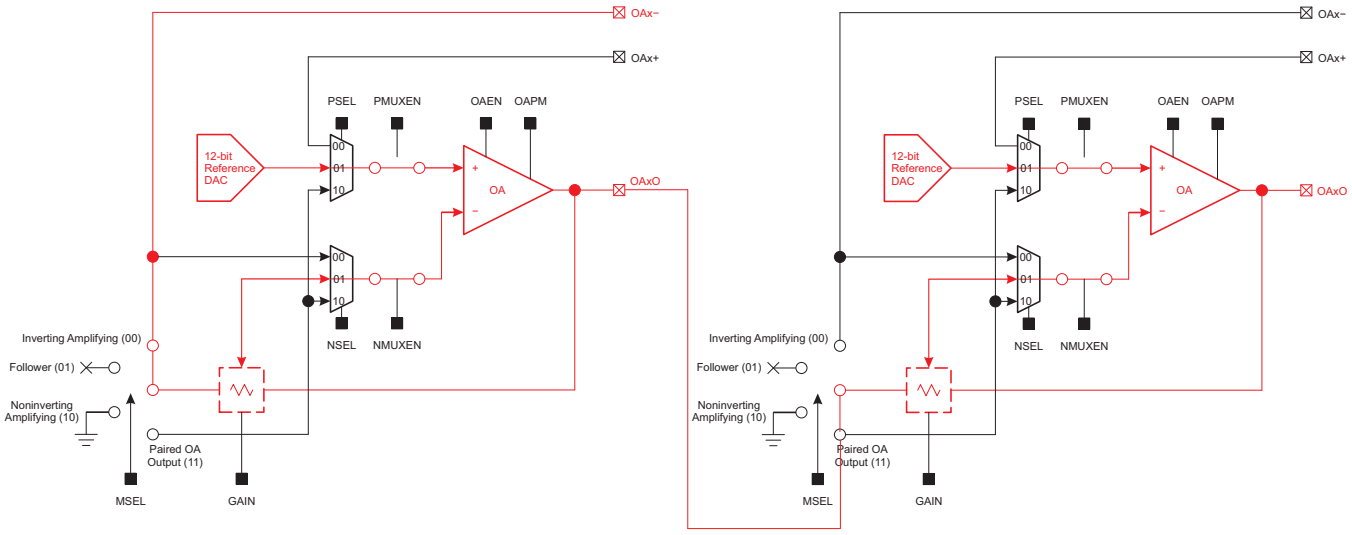

Figure 11. Smart Analog Combo Cascading Example 2

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Figure 12 shows the oscilloscope waveform of SAC cascading example 2. Channel 1 is the input signal of first stage SAC. Channel 2 is the output signal of first stage SAC. Channel 3 is the output of second stage SAC. As Figure 12 shows, the input signal is amplified twice with inverting. After inverting amplification twice, the output signal has the same phase as the input signal, and its amplitude is 4 times the amplitude of the input signal. The first stage amplifier amplifies the signal by 2 times, and the second amplifier amplifies the signal by 2 times.

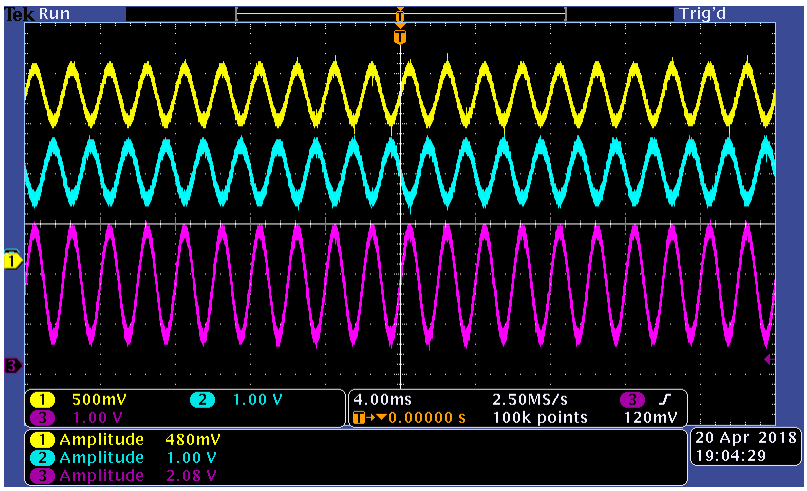

Figure 12. Smart Analog Combo Cascading Waveform 2

3.2 Smart Analog Combo Interconnection With Other Peripherals

In addition to the interconnection between two SAC modules, the MSP430 MCU also supports flexible interconnection between the SAC and other peripherals. As described in Section 2.5, the internal shared reference and timer output are connected to the SAC built-in DAC. The internal shared reference can be used as the DAC voltage reference, and the timer can be used as trigger source for DAC to load data. Besides internal shared reference and timer, SAC is also connected other peripherals like transimpedance amplifier (TIA), enhanced comparator (eCOMP) and ADC.

The peripheral interconnection is device-specific, and Figure 13 shows the interconnection of SAC0, SAC2, eCOMP0, and ADC12 in the MSP430FR2355 MCU. The SAC0 output and the SAC2 output are connected to the two eCOMP0 input channels. This brings some benefit for signal conditioning by comparing the amplifier output and converting the analog output into a digital output. The SAC0 output is also internally connected to ADC channel A1. SAC1 and SAC3 have interconnections with eCOMP1 and ADC that are similar to the interconnections of SAC0 and SAC2. With these interconnections in the MSP430FR2355 MCU, it is possible to achieve full signal chain implementation without any external components or external connections. This kind of one-chip solution helps to save BOM cost and to optimize PCB size.

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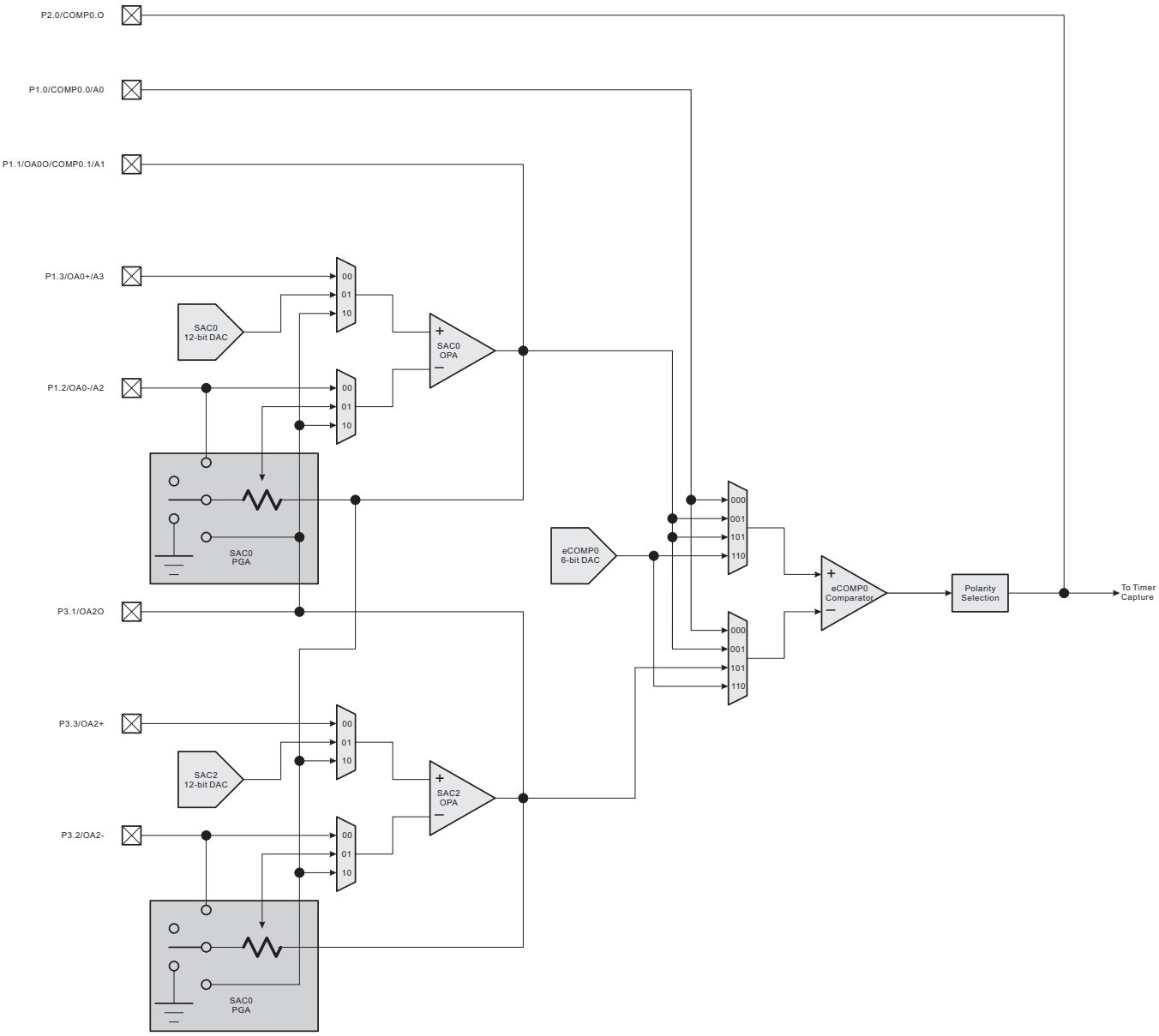

Figure 13. Smart Analog Combo Interconnection With eCOMP and ADC

4 Smart Analog Combo Use Cases in Sensing Applications

4.1 Use Smart Analog Combo in Smoke Detector

This section describes how to use SAC in real sensing and measurement applications. Smoke detector and current loop are taken as two application examples. Figure 14 shows SAC use case in smoke detector application. The first-stage SAC is configured in TIA mode, and the second-stage SAC is configured in noninverting PGA mode. The DAC is used in the first-stage SAC to provide bias voltage so the output swing limitation can be avoid. The output current of the infrared radiation (IR) receiver runs through the TIA to convert the output current of the IR receiver into an analog voltage. This analog voltage is amplified by the second-stage amplifier and then measured by the ADC on the MSP430 MCU.

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The SAC supports a picoamp-level low-leakage input that improves the accuracy of current measurement. To detect currents in the range of picoamps, the feedback resistor R_1 must be in the range of megaohms. Leveraging the interconnection of two SAC modules, the layout to build this kind of SAC cascading is relatively simple. The smoke detector application is constructed to minimize current consumption. The SAC modules are disabled with internal control registers when IR detection is finished. When the SAC modules are turned off, they consume no current. To improve measurement accuracy and avoid false alarms, some smoke detectors include two IR emitters with different wavelengths. The MSP430FR2355 MCU is suitable for this kind of smoke detector, as it integrates four SAC modules, which make it possible to achieve two-channel IR detection on one chip. Smoke detectors are only one of the IR sensing applications. For more details about IR sensing, see the MSP430FR2311 Microcontroller IR Reflection Sensing Reference Design.

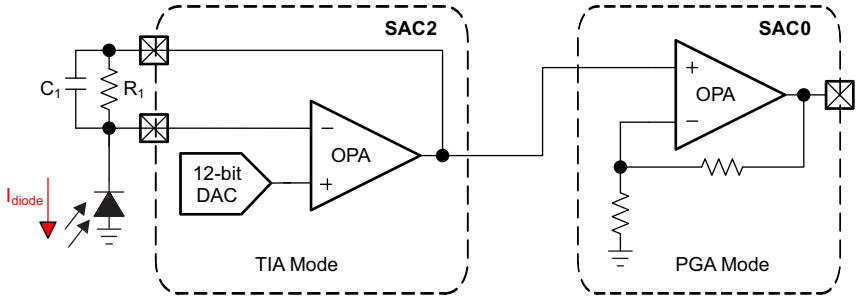

Figure 14. Use Smart Analog Combo in Smoke Detector

4.2 Use Smart Analog Combo in Current Loop

4- to 20-mA current loop is a standard for transmitting remote sensor information to programmable logic controllers over long distances in industrial process monitoring, control, and automation applications. Using the capabilities of the SAC, current loop application designs can have flexible analog configuration while saving BOM cost and PCB size. Figure 15 shows the SAC use case in a 4- to 20-mA current loop application. The first-stage SAC is configured in DAC mode and works as a voltage generator. The second-stage SAC is configured in general-purpose mode and connected with external resistor and transistor. The output of the first-stage SAC is connected to the positive input of second-stage SAC. The second-stage SAC controls the gate voltage of the external transistor and converts the voltage input into a current output. The current value I_{Loop} is determined by the 12-bit DAC output voltage and the resister values. Setting R_1 = 99 kΩ, R_2 = 100 Ω, R_{IN} = 100 kΩ, then I_{Loop} is calculated by Equation 1.

$$I_{Loop} = \frac{V_{DACOUT}}{R_{IN}} \times \left(1 + \frac{R_1}{R_2}\right) = \frac{V_{DACOUT}}{100\ k\Omega} \times \left(1 + \frac{99\ k\Omega}{100\ \Omega}\right) = \left(\frac{DAC_{CODE}}{2^{12}} \times 25\right) mA \quad (1)$$

The TI Design 4- to 20-mA Loop-Powered RTD Temperature-Transmitter Reference Design Using Smart Analog Combo of MSP430™ MCUs is based on the MSP430FR2355 MCU and demonstrates how to use the SAC in a current loop application.

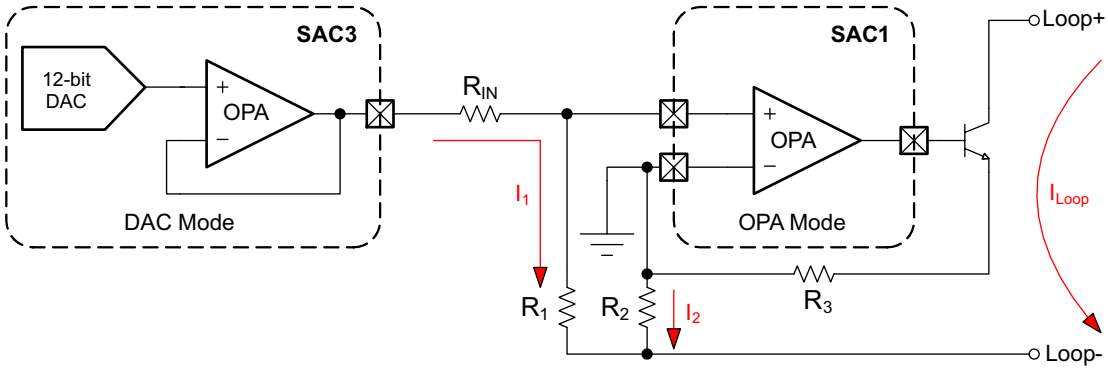

Figure 15. Use Smart Analog Combo in Current Loop

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5 References

1. MSP430FR4xx, MSP430FR2xx Family User's Guide
2. MSP430FR4xx, MSP430FR2xx Mixed Signal Microcontroller data sheet
3. Single-Supply Op Amp Design Techniques
4. MSP430 DriverLib for MSP430FR2xx_4xx Devices User's Guide
5. MSP430FR2311 Microcontroller IR Reflection Sensing Reference Design
6. 4- to 20-mA Loop-Powered RTD Temperature-Transmitter Reference Design Using Smart Analog Combo of MSP430™ MCUs

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