

# ***How to Use the Integrated Operational Amplifiers on MSP430FR2311***

## ABSTRACT

In sensing applications, operational amplifiers are often needed to condition (for example, to amplify and filter) the analog sensor output so that it can be properly sampled by the analog-to-digital converter on the MCU. This application report provides a guide to set up the integrated operational amplifiers (TIA and SAC\_OA) on the MSP430FR2311 microcontroller. Examples are provided for using the integrated operational amplifiers as a transimpedance amplifier for current sensing applications. Considerations for low-power operation are also discussed.

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## 1 Introduction

In many sensing applications, the raw analog output of a sensor must be amplified, filtered, or converted to a voltage to be properly sampled by the analog-to-digital converter (ADC). The digital stream from the ADC is then processed by an MCU to extract the useful information. One example is a transimpedance amplifier. The transimpedance amplifier converts the output current from a sensor to a voltage that is readable by an ADC. Stand-alone operational amplifiers (OAs) are normally used to perform the task. To reduce the cost and design complexity, two configurable operational amplifiers are implemented on MSP430FR2311 mixed signal microcontroller for single chip designs.

This application report describes how to set the MSP430FR2311 control registers to use the integrated OAs as general-purpose OAs. The transimpedance amplifier for the current sensing applications is used as examples to demonstrate the operation. One complete current sensing system example is discussed with consideration for low-power applications. The examples are verified with the [MSP430FR2311 LaunchPad™ development kit](#).

The MSP430FR2311 includes two integrated OAs:

- Transimpedance amplifier (TIA)
- General-purpose OA in the Smart Analog Combo module (SAC\_OA)

There are two major differences between those two OA modules. The first difference is the input bias current. On the TSSOP16 package, there is a dedicated pin for the negative input of the TIA module, and the input bias current is much lower compared to input pins that are multiplexed with other functions. The second difference is input voltage range. The inputs of the TIA module support only half-rail voltage, while the inputs of the SAC\_OA module support rail-to-rail voltage.

In applications that require wider bandwidth, a second stage of OA is required. The integrated OAs on the MSP430FR2311 make design simple with the internal connections between the two OAs and ADC. The user can choose the TIA module for the first stage and the SAC\_OA as the second stage. The TIA output is internally connected to the SAC\_OA input. The SAC\_OA output is internally connected to the ADC input. No external connection is needed, which not only reduces cost but also improves signal quality. Although the OA outputs are internally connected to next stage of processing, they must be routed to the external pins because the external feedback network is required.

The electrical characteristics of the integrated OAs can be found in the [MSP430FR2311 data sheet](#).

For more details about how to design with operational amplifiers, refer to the following application reports:

[An Applications Guide for Op Amps](#)

[Handbook of Operational Amplifier Applications](#)

For more details about transimpedance amplifiers, refer to the following application reports:

[Transimpedance Amplifiers \(TIA\): Choosing the Best Amplifier for the Job](#)

[Transimpedance Considerations for High-Speed Operational Amplifiers](#)

The user must verify the sensor specifications and working conditions for application so that the integrated OAs are configured properly.

## 2 Configuration of the Integrated Operational Amplifiers

This section describes how to set up the MSP430FR2311 control registers to enable the integrated operational amplifiers as general-purpose operational amplifiers. There are two steps in setting up an integrated OA to work as a general-purpose OA.

- Enable and configure the OA module.
- Configure the pin multiplexing to enable required OA functions on the external pins.

### 2.1 Configuration of SAC\_OA

Figure 1 shows the block diagram of SAC\_OA. The black squares are the control bits in the SAC0OA register. In addition to an external pin, the output of the SAC\_OA is internally connected to inputs of the compare (eCOMP) and analog-to-digital converter (ADC) modules for further processing. The internal connections save pins so that signal is not routed out and then back into the device, which also can be advantageous in respect to noise. The control registers of the eCOMP and ADC modules must be configured to use this signal as input.

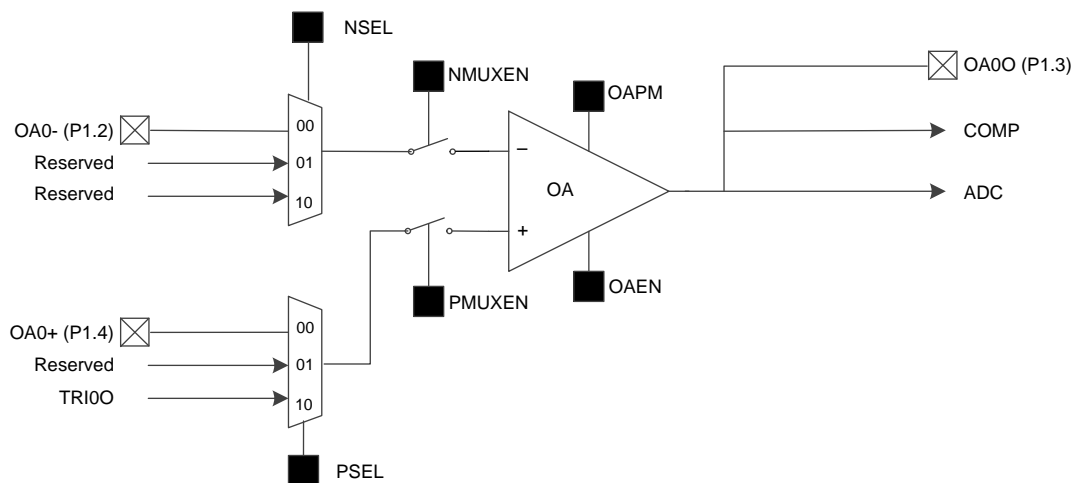


Figure 1. SAC\_OA Block Diagram

To enable SAC\_OA as a general-purpose operational amplifier, the OAEN, PMUXEN, and NMUXEN bits must be set in the SAC0OA register. Configure the OAPM bit to select high-speed or low-speed mode according to the application requirements. The high-speed mode enables faster slew rate at the cost of higher power consumption. The PSEL bits can be configured to connect the positive input to the external pin or TIA output.

Figure 2 shows the definition of the control register SAC0OA. For example, a value of 0x0588 must be written to the SAC0OA register to set up SAC\_OA inputs to external pins and set SAC\_OA in low-power low-speed mode.

15	14	13	12	11	10	9	8
Reserved					SACEN	OAPM	OAEN
r0	r0	r0	r0	r0	rw-(0)	rw-(0)	rw-(0)
7	6	5	4	3	2	1	0
NMUXEN	Reserved	NSEL	PMUXEN	Reserved	PSEL		
rw-(0)	r0	rw-(0)	rw-(0)	rw-(0)	r0	rw-(0)	rw-(0)

Figure 2. SAC0OA Register (Address 0x0C80)

The I/O pins on MSP430FR2311 are multiplexed with multiple module functions. The GPIO port control registers P1SEL0 and P1SEL1 must be configured to enable the SAC\_OA function on the external pins. Figure 3 and Figure 4 show the definition of the P1SEL0 and P1SEL1 registers, respectively. Bits 2, 3, and 4 must be set in both the P1SEL0 and P1SEL1 registers to enable operational amplifier function on the external I/O pins.

7	6	5	4	3	2	1	0
P1SEL0							
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

**Figure 3. P1SEL0 Register (Address 0x020A)**

7	6	5	4	3	2	1	0
P1SEL1							
rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0	rw-0

**Figure 4. P1SEL1 Register (Address 0x020C)**

As an example, use the code sequence in [Example 1](#) to enable SAC\_OA in low-speed mode with MSPWare driverlib APIs. In this example, all SAC\_OA pins are routed to external I/O pins.

### Example 1. Code Example for Configuring SAC\_OA

```
//Enable op amp functions on external pins
GPIO_setAsPeripheralModuleFunctionInputPin (GPIO_PORT_P1,
      GPIO_PIN2 | GPIO_PIN3 | GPIO_PIN4, GPIO_TERNARY_MODULE_FUNCTION);

//Select external pins for both positive and negative inputs
SAC_OA_init(SAC0_BASE, SAC_OA_POSITIVE_INPUT_SOURCE_EXTERNAL,
SAC_OA_NEGATIVE_INPUT_SOURCE_EXTERNAL);

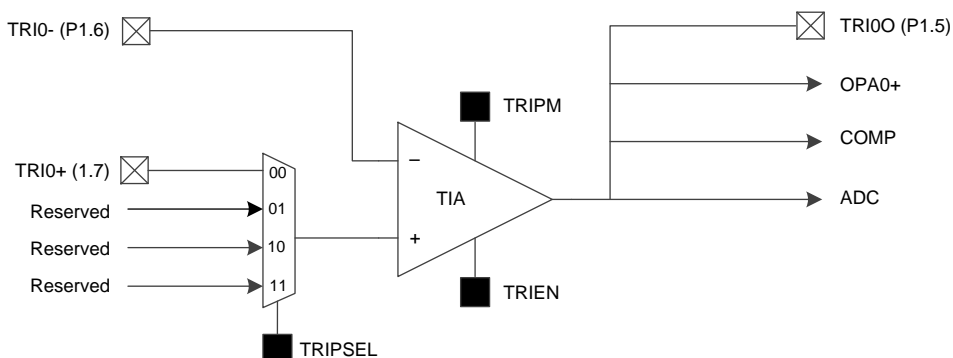
//Select low speed and low power mode
SAC_OA_selectPowerMode(SAC0_BASE, SAC_OA_POWER_MODE_LOW_SPEED_LOW_POWER);

// Enable OA
SAC_OA_enable(SAC0_BASE);

// Enable SAC
SAC_enable(SAC0_BASE);
```

## 2.2 Configuration of TIA

[Figure 5](#) shows the block diagram of the TIA module. The black squares are the control bits in the TRICTL register. In addition to an external pin, the output of TIA is internally connected to inputs of the eCOMP, ADC, and SAC\_OA modules for further processing. The control registers of those modules must be configured to use this signal as input.


**Figure 5. TIA Block Diagram**

To enable TIA as a general-purpose operational amplifier, the TRIEN bit must be set in the TRICTL register. Configure the TRIPM bit to select high-speed or low-speed mode. A value of 0x01 must be written to the TRICTL register to enable TIA as a general-purpose operational amplifier in low-speed mode. To support faster slew rate, the high-speed mode can be set by writing a value of 0x3 to the TRICTL register. The high-speed mode consumes more power than the low-speed mode. [Figure 6](#) shows the definition of the TRICTL register.

15	14	13	12	11	10	9	8
Reserved							
r-0	r-0	r-0	r-0	r-0	r-0	r-0	r-0
7	6	5	4	3	2	1	0
TRIPSEL		Reserved				TRIPM	TRIEN
rw-(0)	rw-(0)	r-0	r-0	r-0	r-(0)	rw-(0)	rw-(0)

**Figure 6. TRICTL Register (Address 0x0F00)**

The GPIO port control register P1SEL0 and P1SEL1 must be configured to enable the TIA function on the external pins. Bits 5, 6, and 7 must be set in both P1SEL0 and P1SEL1 registers to enable the TIA function on the external I/O pins.

As an example, the code sequence in [Example 2](#) can be used to set up TIA in low-speed mode with MSPWare driverlib APIs.

### **Example 2. Code Example for Configuring TIA**

```
//Configure Op-Amp functionality for the external pins
GPIO_setAsPeripheralModuleFunctionInputPin(GPIO_PORT_P1,
                                           GPIO_PIN5 | GPIO_PIN6 | GPIO_PIN7,
                                           GPIO_TERNARY_MODULE_FUNCTION);

//Select low power low speed mode
TRI_selectPowerMode(TRI0_BASE, TRI_LOW_SPEED_LOW_POWER);

//Enable TIA
TRI_enable(TRI0_BASE);
```

## **3 Application Examples**

When an integrated OAs is enabled and signals are routed to external I/O pins, the module can be used as a stand-alone OA. The functionality of the amplifier is determined by the feedback network. The following examples are based on the circuit of the MSP430FR2311 LaunchPad development kit.

### **3.1 SAC\_OA as a Transimpedance Amplifier**

In many applications, the sensing element (a photodiode, for example) is a current source. A transimpedance amplifier is required to convert the sensor output current to voltage so that it can be read by the ADC module.

A transimpedance amplifier composed of the SAC\_OA module (see [Figure 7](#)).

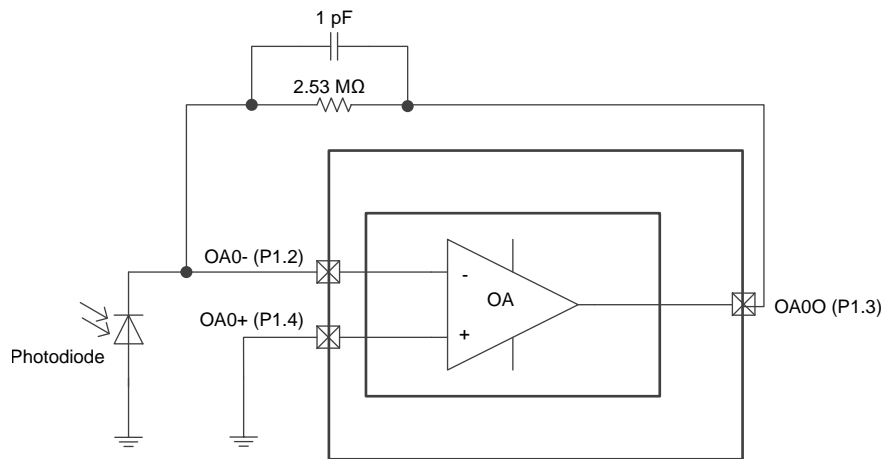


Figure 7. Transimpedance Amplifier With SAC\_OA

The gain of the transimpedance amplifier is purely determined by the value of the feedback resistor when the input bias current of the operational amplifier is negligible. For the circuit in Figure 8, a voltage of 2.5 V is observed at the OA0O pin when the photodiode generates an output of 1  $\mu$ A. The 1-pF bypass capacitor enables a low-pass filter with a pole at 63 kHz to eliminate potential oscillation at high frequencies.

Figure 8 shows the op amp output voltage with 1- $\mu$ A input current. For this example, the photodiode on the MSP430FR2311 LaunchPad development kit is replaced by a current source. The current source is constructed by a function generator with a 1-M $\Omega$  resistor in series. Figure 9 shows the op amp output voltage with 50-nA input current. The input waveform is on Channel 2, and the output is on Channel 1.

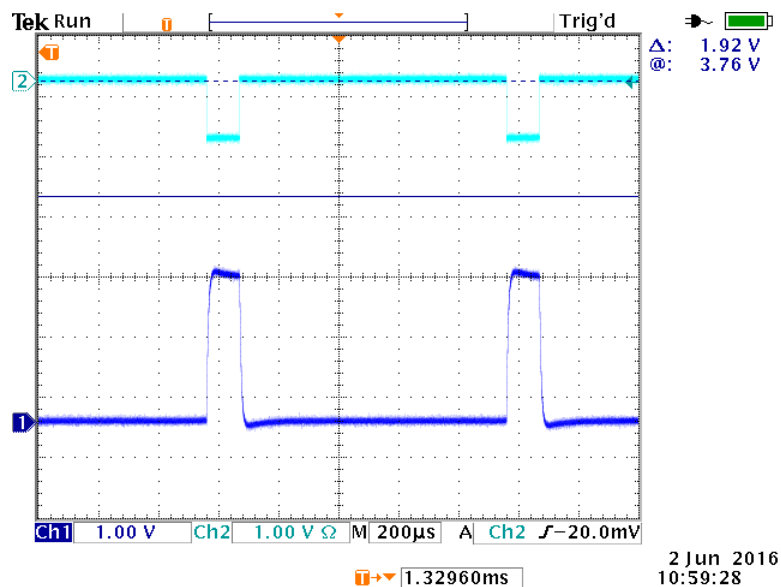


Figure 8. Output Voltage With 1- $\mu$ A Input Current

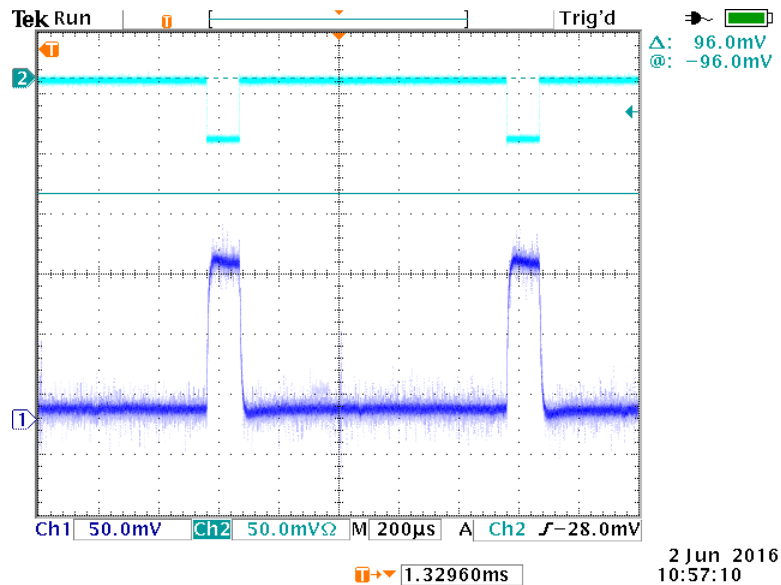


Figure 9. Output Voltage With 50-nA Input Current

### 3.2 TIA Module as a Transimpedance Amplifier

The transimpedance amplifier in Figure 10 is the same as in Figure 7 except that the operational amplifier is replaced by the TIA module. On the TSSOP16 package, the TIA module is the preferred choice for a transimpedance amplifier due to the small input bias current on the TRI0- pin. A user can take advantage of the low input bias current when interfacing a sensor with low output current.

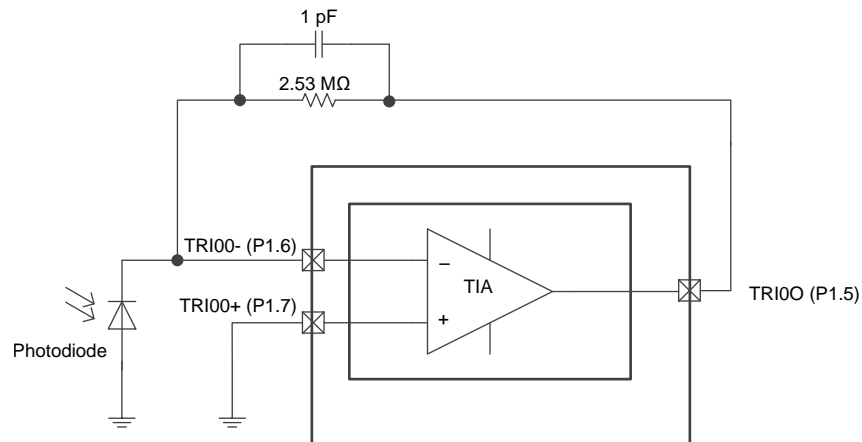


Figure 10. Transimpedance Amplifier With TIA

Figure 11 shows the output voltage with 1- $\mu$ A input current pulses. On the MSP430FR2311 LaunchPad, the phot diode is replaced by a current source. Jumpers are removed to disconnect the SAC\_OA pins from input. Then two jumper wires are used to connect the feedback resistor and current source to the TIA negative input and output. The TIA positive input is tied to ground via a jumper wire. The noise level is high in the output due to long jumper wires. In a real application, the signal traces to the op amp must be as short as possible to minimize noise.

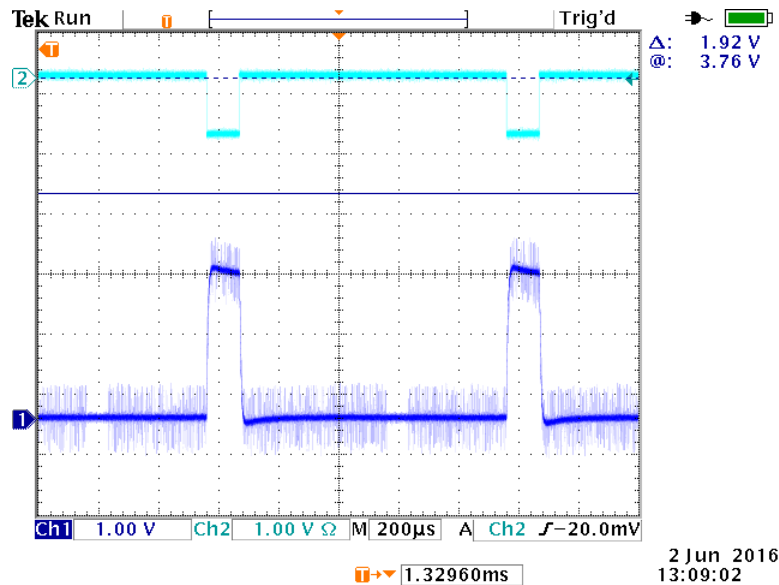


Figure 11. Output Voltage With 1- $\mu$ A Input Current

### 3.3 A Current Sensing System Demo

The out-of-box demo provided with the MSP430FR2311 LaunchPad development kit implements a complete current sensing system example. It shows how to use the integrated op-amp (SAC\_OA) as a transimpedance amplifier along with the timer, ADC, and external LED to implement a light sensor for ultra-low-power applications.

Figure 12 shows the block diagram of the demo. The transimpedance amplifier is made of the SAC\_OA module. It converts the current from the photodiode to a voltage. 1- $\mu$ A input current produces a voltage of 2.5 V. This voltage is then read by the analog-to-digital converter (ADC) and fed to a timer module to drive an external LED with PWM. The duty cycle of the PWM is proportional to the current from the photodiode. As more light reaches the photodiode, the LED becomes brighter.

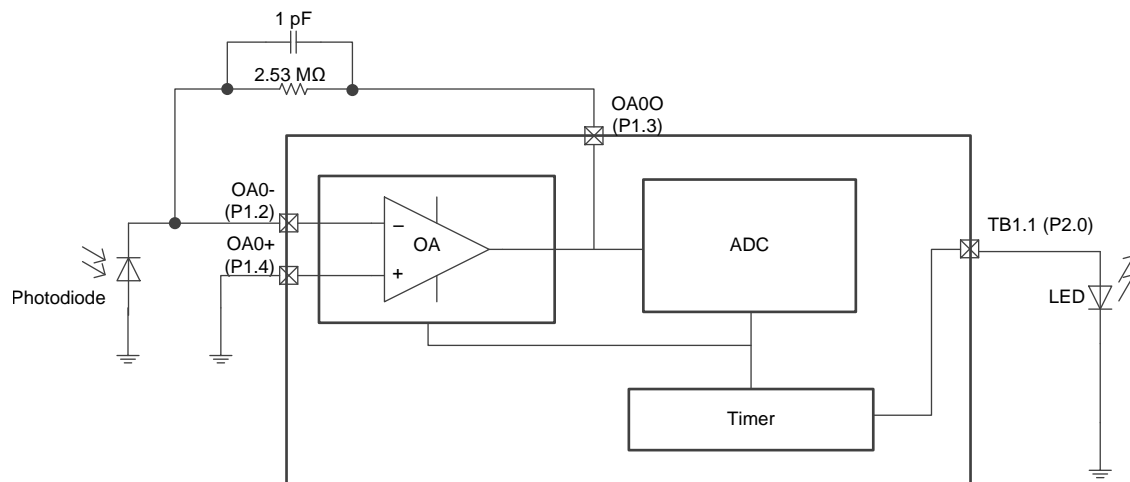


Figure 12. Block Diagram of the Out-of-Box Demo

To demonstrate how to reduce power consumption, the device is kept in lower-power mode most of time. A timer is set up to wake up the device every 50 ms for the measurements. The complete Code Composer Studio™ IDE project for the demo can be downloaded from the [TI web site](#).



Figure 13 shows the output voltage of the transimpedance amplifier when it is dynamically enabled and disabled. After the OA is enabled, a small delay is needed before starting the ADC module so that the ADC module does sample the transient pulse when the op amp is enabled.

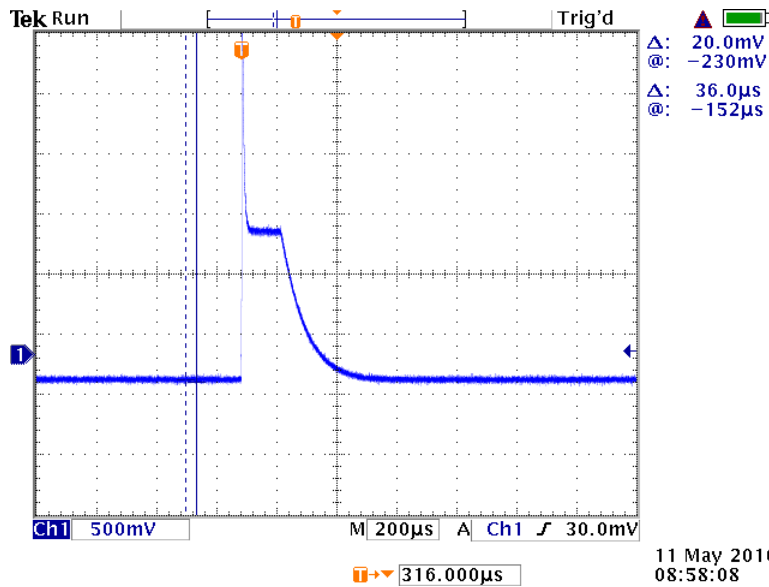


Figure 13. Output Voltage When the Op Amp is Dynamically Turned On and Off

Figure 14 shows the power consumption of the demo. This data was captured using EnergyTrace™ technology. The power profile data indicates a battery life of 380 days when a CR2032 battery is used.

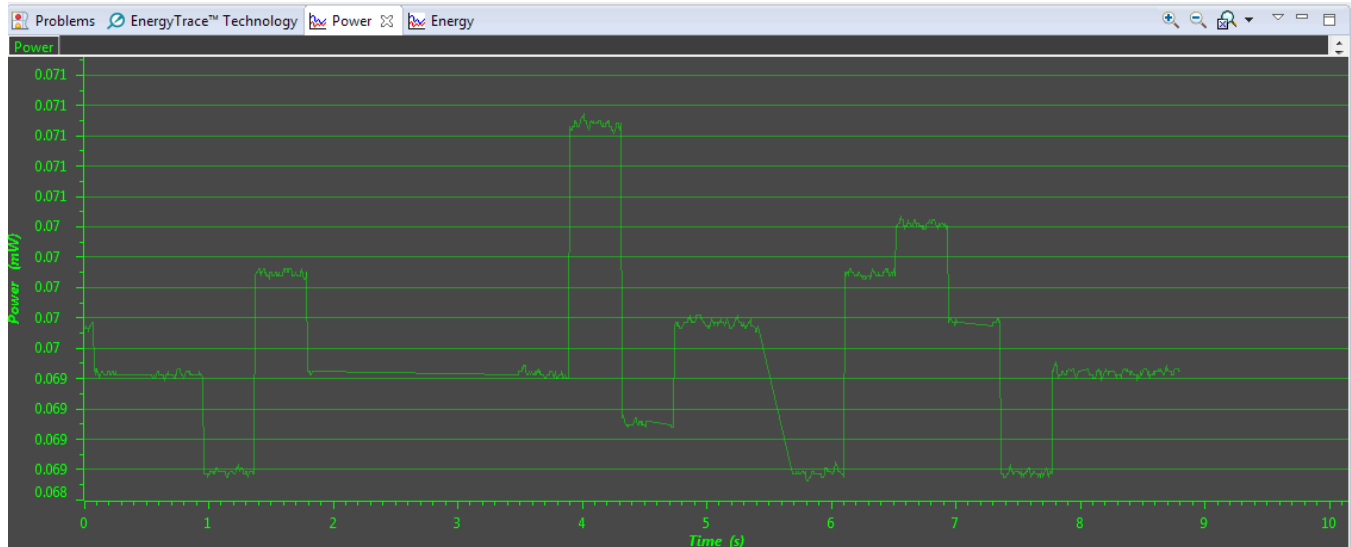


Figure 14. Power Consumption of the Out-of-Box Demo

This demonstration provides functional blocks that can be used for applications such as smoke detectors and gas detectors.

## 4 References

1. [\*MSP430FR231x Mixed-Signal Microcontrollers\*](#)
2. [\*MSP430FR4xx and FR2xx Family User's Guide\*](#)
3. [\*MSP430FR2311 LaunchPad™ Development Kit \(MSP-EXP430FR2311\) User's Guide\*](#)
4. [\*AN-20 An Applications Guide for Op Amps\*](#)
5. [\*Handbook of Operational Amplifier Applications\*](#)
6. [\*Transimpedance Amplifier \(TIA\): Choose the Best Amplifier for the Job\*](#)
7. [\*Transimpedance Considerations for High-Speed Amplifiers\*](#)

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