AN13508

Operational Amplifier (OPAMP) Usage on LPC553x/LPC55S3x

Rev. 2 — 20 November 2023 Application note

Document information

Information	Content
Keywords	AN13508, OPAMP, LPC553x/LPC55S3x
Abstract	NXP LPC553x/LPC55S3x series have new analog function modules, including OPAMP (Operational Amplifier).

1 Introduction

NXP LPC553x/LPC55S3x series have new analog function modules, including Operational Amplifier (OPAMP).

OPAMP is an electronic integrated circuit, which contains a multistage amplifier circuit. Its input stage is a differential amplifier circuit. It has high input resistance and the ability to suppress zero drift.

An ideal OPAMP contains the following characteristics:

- Input current IB = 0
- Input offset voltage VE = 0
- Input impedance ZIN = ∞
- Output impedance ZOUT = 0
- Gain a = ∞

To simplify the analysis, see Figure 1 for an ideal OPAMP.

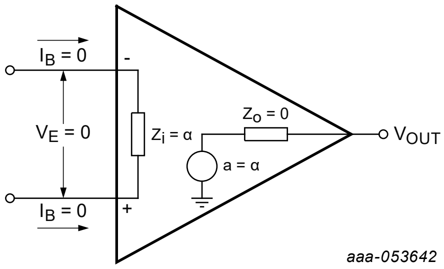

Figure 1. An ideal OPAMP

2 Typical kinds of OPAMP

2.1 Noninverting OPAMP

Figure 2 shows the noninverting OPAMP connection.

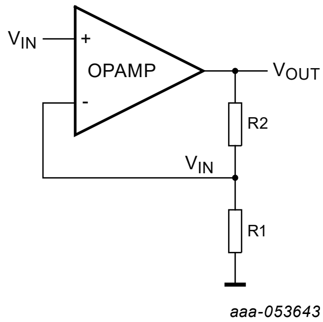

Figure 2. Noninverting OPAMP

Noninverting OPAMP has the input signal connected to its positive input. According to the ideal OPAMP assumptions, Input current IB = 0 and Input offset voltage VE = 0, we can get the equation as below:

$$V_{IN} = V_{OUT} \frac{R1}{R1 + R2} \tag{1}$$

Then:

$$V_{OUT} = V_{IN} \left(1 + \frac{R2}{R1}\right) \tag{2}$$

The output signal is the amplified signal and noninverted from the input signal. The circuit input impedance is an infinite impedance.

2.2 Voltage follower OPAMP

Figure 3 shows the voltage follower OPAMP connection.

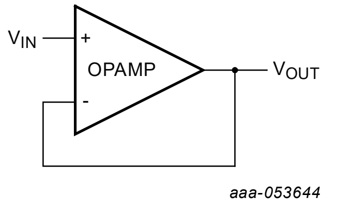

Figure 3. Follower OPAMP

In the noninverting OPAMP, if let the R2 = 0 and remove R1, we can get the equation as below:

$$V_{OUT} = V_{IN} \tag{3}$$

To perform impedance adaptation on input signals, the circuit uses OPAMP as a follower buffer.

2.3 Inverting OPAMP

Figure 4 shows the inverting OPAMP connection.

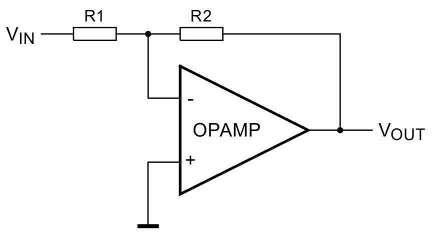

Figure 4. Inverting OPAMP

Inverting OPAMP has the input signal connected to its negative input. According to the ideal OPAMP assumptions, Input current IB = 0 and input offset voltage VE = 0, we can get the equation as below:

$$\frac{V_{IN}}{R1} = -\frac{V_{OUT}}{R2} \tag{4}$$

Then:

$$V_{OUT} = \left(-\frac{R2}{R1}\right)V_{IN} \tag{5}$$

The output signal is the amplified signal and inverted from the input signal.

2.4 Differential OPAMP

Figure 5 shows the differential OPAMP connection.

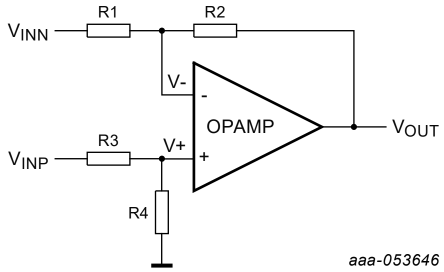

Figure 5. Differential OPAMP

Differential OPAMP amplifies the voltage difference between input signals. According to the ideal OPAMP assumptions, Input current IB = 0 and input offset voltage VE = 0, we can get the equation as below.

From

$$\frac{(V_{INP} - V+)}{R3} = \frac{V+}{R4} \tag{6}$$

We can get

$$V+ = \frac{R4}{R3+R4} V_{INP} \tag{7}$$

From

$$\frac{(V- - V_{INN})}{R1} = \frac{V_{OUT} - V-}{R2} \tag{8}$$

We can get

$$V_{OUT} = \frac{R1+R2}{R1} V- - \frac{R2}{R1} V_{INN} \tag{9}$$

According to v+ = v-, from Equation 7 and Equation 9, we can get:

$$V_{OUT} = \frac{R1+R2}{R1} \times \frac{R4}{R4+R3} V_{INP} - \frac{R2}{R1} V_{INN} \tag{10}$$

If let R1 = R3, R2 = R4, then:

$$V_{OUT} = \frac{R2}{R1} \left(V_{INP} - V_{INN}\right) \tag{11}$$

In the circuit, the differential signal, (V_{INP} - V_{INN}), is multiplied by the stage gain. The circuit is a differential amplifier. It amplifies only the differential portion of the input signal and rejects the common mode portion of the input signal.

The differential amplifier strips off or rejects the common mode signal. This circuit configuration is often employed to strip DC or injected common mode noise off a signal.

2.5 Differential with offset OPAMP

Figure 6 shows the differential with offset OPAMP connection.

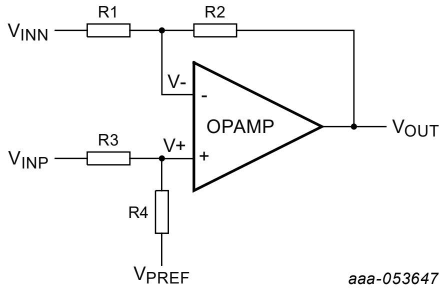

Figure 6. Differential with offset OPAMP

In the differential OPAMP amplifies, when R4 connects a VPREF voltage instead of connecting to ground, then the circuit becomes differential with offset OPAMP. According to the ideal OPAMP assumptions: Input current IB = 0 and input offset voltage VE = 0, we can get the equations as below.

From:

$$\frac{V_{INP} - V+}{R3} = \frac{V+ - V_{PREF}}{R4} \quad (12)$$

We can get:

$$V+ = \frac{R4}{R3+R4} V_{INP} + \frac{R3}{R3+R4} V_{PREF} \quad (13)$$

From:

$$\frac{(V- - V_{INN})}{R1} = -\frac{V_{OUT} - V-}{R2} \quad (14)$$

We can get:

$$V_{OUT} = \frac{R1+R2}{R1} V- - \frac{R2}{R1} V_{INN} \quad (15)$$

According to v+ = v-, from Equation 13 and Equation 15, we can get:

$$V_{OUT} = \frac{R1+R2}{R1} \times \frac{R4}{R3+R4} V_{INP} - \frac{R2}{R1} V_{INN} + \frac{R1+R2}{R1} \times \frac{R3}{R3+R4} V_{PREF} \quad (16)$$

3 OPAMP on LPC553x/LPC55S3x

The features of OPAMP on LPC553x/LPC55S3x include:

- It contains three OPAMPs, supporting a PGA amplifier.
- It configures registers with an optional noninverting or inverting gain application to select different gains.
- The module is applicable to the signal processing stage before SARADC.

The specifications of OPAMP on LPC553x/LPC55S3x include:

- DC open loop voltage gain 110 dB
- Slew rate 2 V/us (low-noise mode), 5.5 V/us (high-speed mode)
- Unity gain bandwidth: 3 MHz (low-noise mode), 15 MHz (high-speed mode)
- Rail-to-rail input/output (0 - VDDA)
- PGA with negative programmable gain: -1X, -2X, -4X, -8X, -16X, -33X, -64X, positive programmable gain: 1X, 2X, 4X, 8X, 16X, 33X, 64X

The working mode of OPAMP on LPC553x/LPC55S3x includes:

- Standalone (buffer) mode
  Figure 7 shows the OPAMP block diagram.

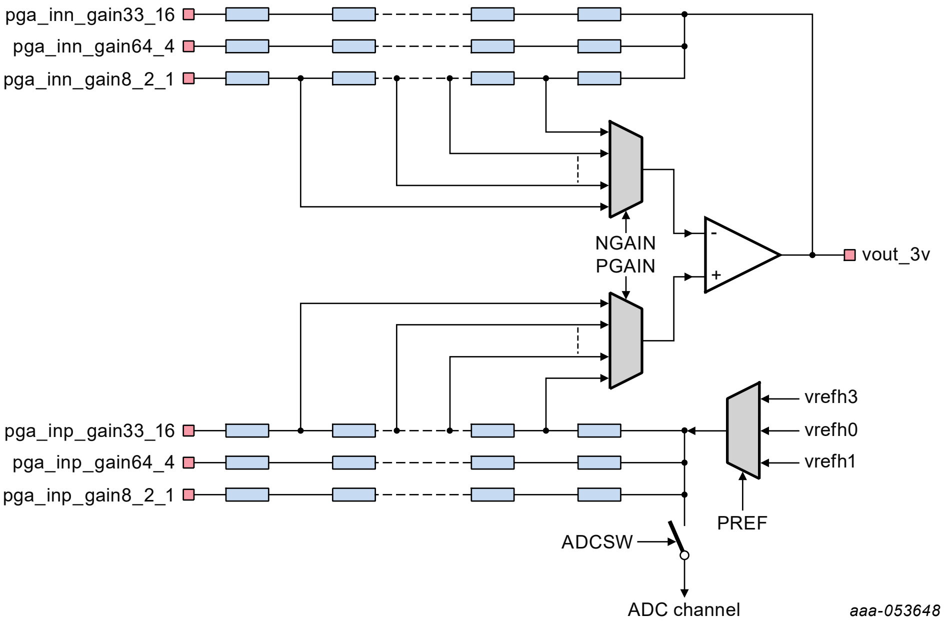

Figure 7. OPAMP block diagram

  To make OPAMP work in the Buffer mode, set register `OPAMP_CTR bit[26-24] "NGAIN"` to `000` - Buffer. In this mode, OPAMP works alone. It has no connection with the internal Res Matrix, just pulling out `OPAMPx_INP`, `OPAMPx_INN`, and `OPAMPx_Out` pins for users. Users can connect outside circuit on these pins to apply functions as required.
- Programmable Gain Amplifier (PGA) mode
  To make OPAMP work on PGA mode, don't set register `OPAMP_CTR bit[26-24] NGAIN` to `000` - Buffer and don't set `bit[22-20] NGAIN` to `000` - Reserved.
  In this mode, OPAMP connects with the internal Res Matrix and amplifies the input voltage according to NGAIN and PGAIN setting value. The amplify principle is illustrated in Section 5.

4 LPC553x/LPCS553x OPAMP pin description

LPC553x/LPC55S3x OPAMP pins include:

- `OPAMP0_INP/PIO0_8` pin, with the default `OPAMP0_INP`
- `OPAMP1_INP/PIO0_27` pin, with the default `OPAMP1_INP`
- `OPAMP2_INP/PIO2_1` pin, with the default `OPAMP2_INP`
- `OPAMP0_INN` - Dedicated pin
- `OPAMP1_INN` - Dedicated pin
- `OPAMP2_INN` - Dedicated pin
- `OPAMP0_Out/PIO1_9` pin, with the default `OPAMP0_Out`
- `OPAMP1_Out/PIO2_14` pin, with the default `OPAMP1_Out`
- `OPAMP2_Out/PIO2_2` pin, with the default `OPAMP2_Out`

5 Usage of OPAMP on LPC553x/LPCS553x

5.1 Using OPAMP as follower OPAMP

To make OPAMP work in the Buffer mode, set register `OPAMP_CTR bit[26-24] NGAIN` to `000` - Buffer.

Connect `OPAMPx_INN` to `OPAMPx_OUT`, and we can get:

$$V_{OUT} = V_{INP} \tag{17}$$

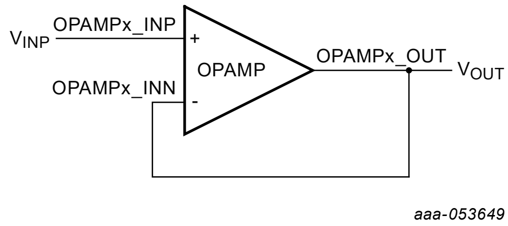

Figure 8. Using OPAMP as follower OPAMP

5.2 Using OPAMP as differential with Offset OPAMP

When set to PGA mode, the OPAMP on LPC553x/LPC55S3x uses Res Matrix to get NGAIN, PGAIN, as shown in Figure 9.

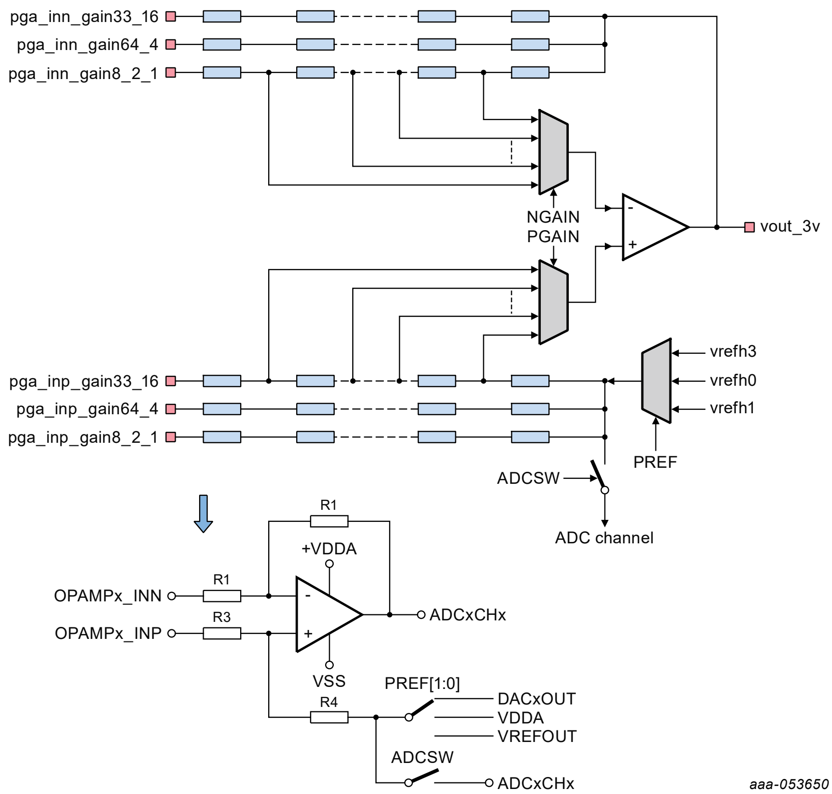

Figure 9. LPC553x/LPC55S3x OPAMP block diagram and equivalent circuit

The internal Res Matrix is equivalent to R1, R2, R3, R4.

R2/R1 = NGAIN

R4/R3 = PGAIN

NGAIN and PGAIN with gain rate x1, x2, x4, x8, x16, x33, and x64 are as shown in Figure 10.

NGAIN(1) = 1/1 (R2/R1)	PGAIN(1) = 1/1 (R4/R3)
NGAIN(2) = 2/1	PGAIN(2) = 2/1
NGAIN(3) = 4/1	PGAIN(3) = 4/1
NGAIN(4) = 8/1	PGAIN(4) = 8/1
NGAIN(5) = 16/1	PGAIN(5) = 16/1
NGAIN(6) = 33/1	PGAIN(6) = 33/1
NGAIN(7) = 64/1	PGAIN(7) = 64/1

Figure 10. NGAIN and PGAIN with gain rate x1, x2, x4, x8, x16, x33, x64

According to Equation 16 concluded from the above analysis and make:

R2/R1 = NGAIN

R4/R3 = PGAIN

We can get:

$$V_{OUT} = \frac{NGAIN+1}{1+\frac{1}{PGAIN}} V_{INP} - NGAIN \times V_{INN} + \frac{1+NGAIN}{1+PGAIN} V_{PREF} \quad (18)$$

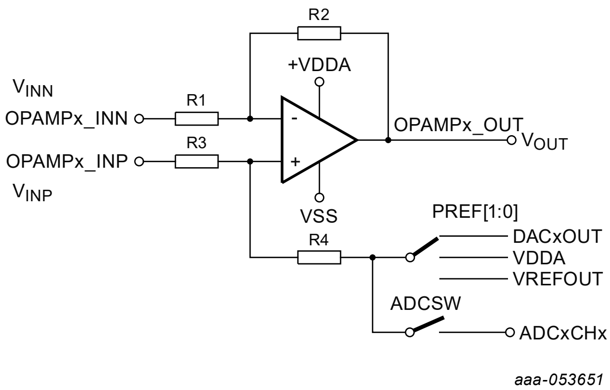

Figure 11. Using OPAMP as differential with Offset OPAMP

5.3 Using OPAMP as differential OPAMP

LPC553x/LPC55S3x OPAMP works in the PGA mode.

To make OPAMP use DAC0OUT as V_{PREF}, set register `OPAMP_CTR bit[18-17] PREF` to `00` - Select **vrefh3**.

To set V_{PREF} to 0, make `DACxOUT` output as 0.

According to Equation 18, we can get:

$$V_{OUT} = \frac{NGAIN+1}{1+\frac{1}{PGAIN}} V_{INP} - NGAIN \times V_{INN} \quad (19)$$

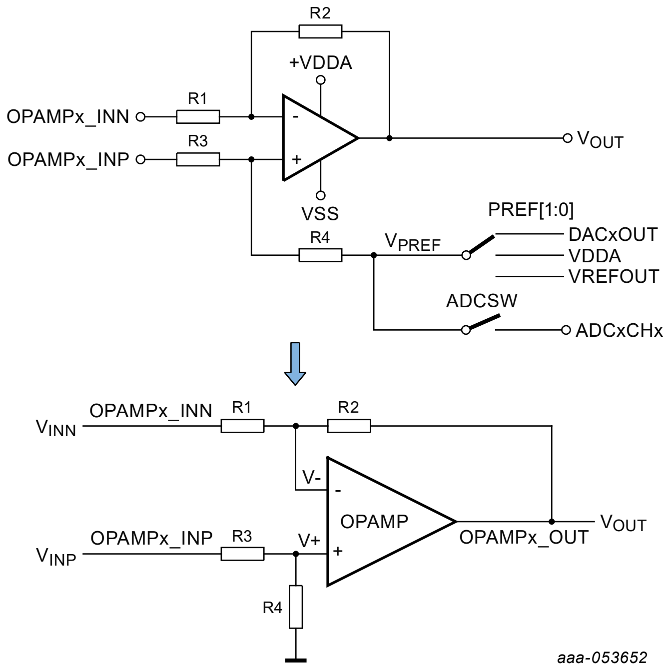

Figure 12. Using OPAMP as differential OPAMP

5.4 Using OPAMP as noninverting OPAMP

LPC553x/LPC55S3x OPAMP works on PGA mode.

To make VPREF become the high-impedance state, connect V_{PREF} to V_{REFOUT}, set register `OPAMP_CTR bit[18-17] PREF` to 10 - Select vrefh1, and disable the V_{REF} module (default). Make $V_{PREF} = V_{INP}$.

Connect V_{INN} to 0.

Then we can get:

$$V_{OUT} = \frac{NGAIN + 1}{1 + \frac{1}{PGAIN}} V_{INP} + \frac{1 + NGAIN}{1 + PGAIN} V_{PREF} \quad (20)$$

$$V_{OUT} = \frac{NGAIN + 1}{1 + \frac{1}{PGAIN}} V_{INP} + \frac{1 + NGAIN}{1 + PGAIN} V_{INP} \quad (21)$$

$$V_{OUT} = \left(1 + NGAIN\right) \times V_{INP} \quad (22)$$

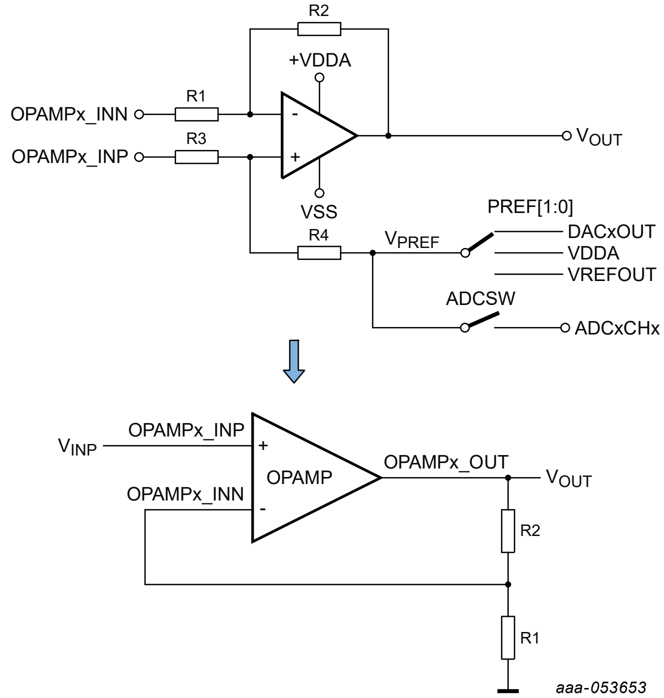

Figure 13. Using OPAMP as Noninverting OPAMP

5.5 Using OPAMP as inverting OPAMP

LPC553x/LPC55S3x OPAMP works in the PGA mode.

To set V_{PREF} at the high-impedance state, connect V_{PREF} to V_{REFOUT} and disable the V_{REF} module (default). Make $V_{PREF} = V_{INP}$.

Connect V_{INP} to 0. Make $V_{PREF} = V_{INP} = 0$.

Then we can get:

$$V_{OUT} = -NGAIN \times V_{INN} \tag{23}$$

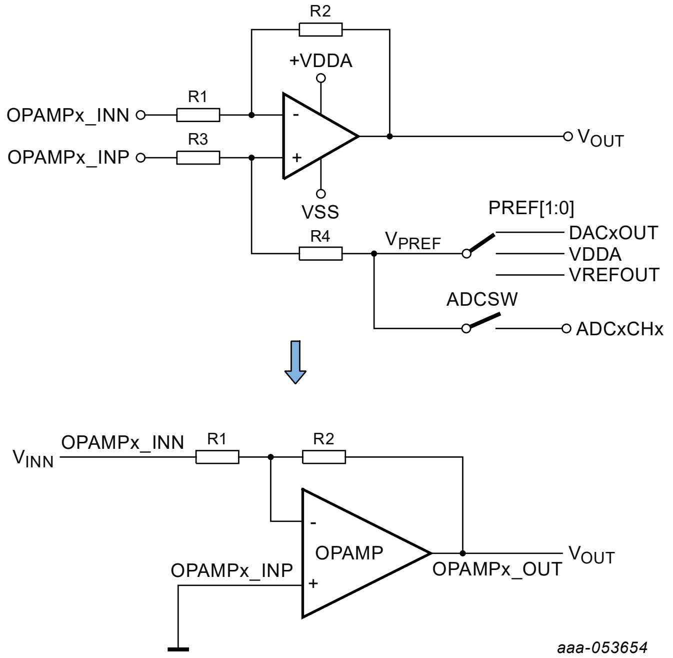

Figure 14. Using OPAMP as inverting OPAMP

6 Demo for OPAMP on LPC553x/LPCS553x

6.1 Demo platform

6.1.1 Hardware

The demo is developed on the LPCXpresso55s36 board.

6.1.2 Software

The demo code is based on SDK_2_14_0_LPCXpresso55S36.

IDE: MDK5.37

6.2 Using LPC553x/LPCS553x OPAMP as differential with Offset OPAMP

This demo illustrates how to use OPAMP on LPC553x/LPC55S3x to work as a differential with Offset OPAMP.

6.2.1 Board connection

Figure 15 shows the board connection.

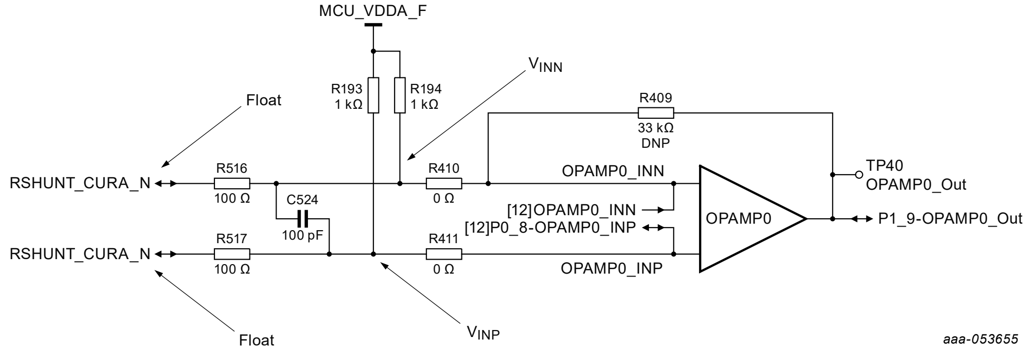

Figure 15. Board connection

According to the board connection, set DAC0OUT as V_{PREF}, and OPAMP can work as differential with Offset OPAMP.

6.2.2 Calculation formula for Demo

`MCU_VDDA_F` produces V_{INP} and V_{INN}, by pulling up resisters `R193` and `R194`.

OPAMP uses DAC0OUT as V_{PREF}. To get V_{PREF} value, OPAMP uses Tera Term to input digital value and then produce an analog value by DAC0.

The gain formula for differential with Offset OPAMP is as shown in Equation 18.

6.2.3 Demo code setup

To make OPAMP use DAC0OUT as V_{PREF}, set register `OPAMP_CTR bit[18-17] PREF` to `00` - Select vrefh3.

To apply the above function, use the configuration demo code at line79 in *OPAMP.c*, as shown in Figure 16.

```
75      OPAMP_GetDefaultConfig(&config);
76      config.posGain = kOPAMP_PosGainNonInvert2X;
77      config.negGain = kOPAMP_NegGainInvert1X;
78      /* Connect REFP to DAC output. */
79      config.posRefVoltage = kOPAMP_PosRefVoltVrefh3; // 3-DAC0, 0-VDDA, 1-Vefout
80      config.enable        = true;
81
82      OPAMP_Init(DEMO_OPAMP_BASEADDR, &config);
83
```

Figure 16. Code configuration for applying DAC0OUT as V_{PREF}

6.2.4 Demo illustration

6.2.4.1 Demo1

To get different V_{OUT}, set NGAIN = 1, PGAIN = 1, and change V_{PREF} by Tera Term

Steps:

1. Set register `OPAMP_CTR bit[26-24] NGAIN` to `001` - Inverting gain application -1X, make NGAIN = 1.
2. Set register `OPAMP_CTR bit[22-20] PGAIN` to `001` - Inverting gain application 1X, make PGAIN = 1.

To apply the above function, use the configuration demo code at line76-77 in *OPAMP.c*, as shown in Figure 17.


```
    OPAMP_GetDefaultConfig(&config);
    config.posGain = kOPAMP_PosGainNonInvert1X;
    config.negGain = kOPAMP_NegGainInvert1X;
    /* Connect REFP to DAC output. */
    config.posRefVoltage = kOPAMP_PosRefVoltVrefh3; // 3-DAC0, 0-VDDA, 1-Vefout
    config.enable        = true;

    OPAMP_Init(DEMO_OPAMP_BASEADDR, &config);

    while (1)
```

Figure 17. Code configuration for NGAIN and PGAIN

Download and run the demo code, as shown in Figure 18.

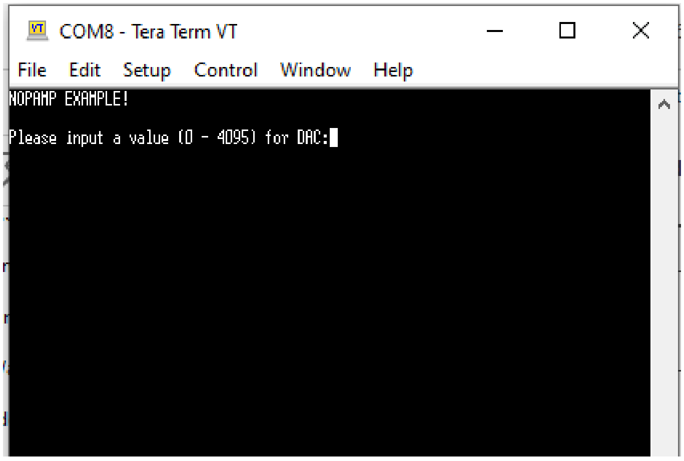

Figure 18. Running page for the demo

To use Tera Term to input VPREF value, perform the following steps.

1. Input 0 for DAC0 by Tera Term to get the offset value for VOUT.
   Measured by multimeter: VINN = 3017 mV, VINP = 3017 mV, VPREF = 3 mV.
   According to Equation 18:
   Calculated V_{OUT_CAL} = V_{PREF} = 3 mV.
   Measured V_{OUT} =50 mV, get offset value for V_{OUT_OFFSET} = V_{OUT} - V_{OUT_CAL} = 47 mV.
   (Test point on EVK board: V_{INN} = J13-3, V_{INP} = J13-1, V_{PREF} = J12-4, V_{OUT} = J7-1)
2. Input 100 for DAC0 by Tera Term.
   Measured V_{INN} = 3022 mV, V_{INP} = 3022 mV, V_{PREF} = 73 mV.
   Calculated V_{OUT_CAL} = V_{OUT_OFFSET} + V_{PREF} = 120 mV.
   Measured V_{OUT} = 120 mV.
   The measured value fits the calculated value.
3. Input 200 for DAC0 by Tera Term.
   Measured V_{INN} = 3029 mV, V_{INP} = 3029 mV, V_{PREF} = 155 mV.
   Calculated V_{OUT_CAL} = V_{OUT_OFFSET} + V_{PREF} = 202 mV.
   Measured V_{OUT} = 202 mV.
   The measured value fits the calculated value.

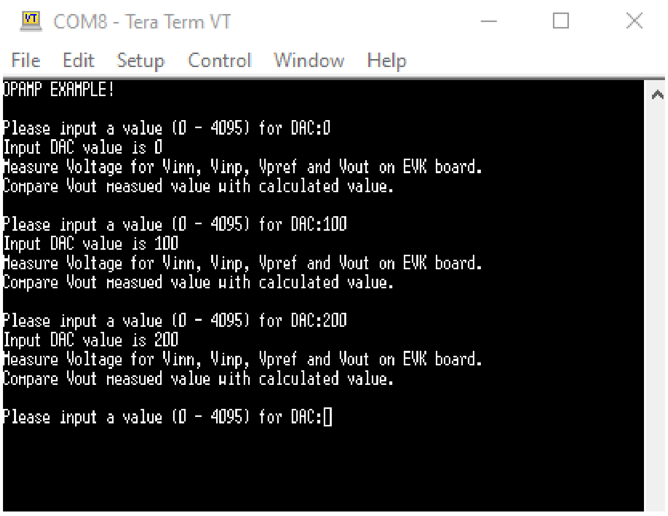

Figure 19. Using Tera Term to input V_{PREF} value

6.2.4.2 Demo 2

To get different V_{OUT}, set NGAIN = 1, PGAIN = 2, and change V_{PREF} by Tera Term.

1. Input 0 for DAC0 by Tera Term to get the offset value for V_{OUT}.
   Measured V_{INN} = 3096 mV, V_{INP} = 3017 mV, V_{PREF} = 3 mV.
   According to Equation 18:
   Calculated V_{OUT_CAL} = 1.333 * V_{INP} – V_{INN} + 0.666 * 3 = 927 mV.
   Measured V_{OUT} =968 mV, get offset value for V_{OUT_OFFSET} = V_{OUT} - V_{OUT_CAL} = 41 mV.
2. Input 100 for DAC0 by Tera Term.
   Measured V_{INN} = 3100 mV, V_{INP} = 3023 mV, V_{PREF} = 73 mV.
   Calculated V_{OUT_CAL} = V_{OUT_OFFSET} + 1.333 * V_{INP} – V_{INN} + 0.666 * 73 = 1020 mV.
   Measured VOUT = 1019 mV.
   The measured value fits the calculated value.
3. Input 200 for DAC0 by Tera Term.
   Measured V_{INN} = 3106 mV, V_{INP} = 3030 mV, V_{PREF} = 155 mV.
   Calculated V_{OUT_CAL} = V_{OUT_OFFSET} + 1.333 * V_{INP} – V_{INN} + 0.666 * 155 = 1077 mV.
   Measured V_{OUT} = 1076 mV.
   The measured value fits the calculated value.

6.2.4.3 Demo 3

To get different V_{OUT}, set NGAIN=1, PGAIN=64, and change V_{PREF} by Tera Term.

1. Input 0 for DAC0 by Tera Term to get the offset value for VOUT.
   Measured V_{INN} = 3248 mV, V_{INP} = 3017 mV, V_{PREF} = 3 mV.
   According to Equation 18:
   Calculated V_{OUT_CAL} = 1.969 * V_{INP} – V_{INN} + 0.031 * 3 = 2692 mV.
   Measured V_{OUT} =2700 mV, get offset value for V_{OUT_OFFSET} = V_{OUT} - V_{OUT_CAL} = 8 mV
2. Input 100 for DAC0 by Tera Term.
   Measured V_{INN} = 3248 mV, V_{INP} = 3023 mV, V_{PREF} = 73 mV.
   Calculated V_{OUT_CAL} = V_{OUT_OFFSET} + 1.969 * V_{INP} – V_{INN} + 0.031 * 73 = 2714 mV.
   Measured V_{OUT} = 2712 mV.
   The measured value fits the calculated value.

3. Input 200 for DAC0 by Tera Term.
   Measured V_{INN} = 3249 mV, V_{INP} = 3030 mV, V_{PREF} = 155 mV.
   Calculated $V_{OUT\_CAL} = V_{OUT\_OFFSET} + 1.969 * V_{INP} – V_{INN} + 0.031 * 155 = 2730$ mV.
   Measured V_{OUT} = 2728 mV.
   The measured value fits the calculated value.
   According to calculation and measurement, the results are reasonable and fit Equation 18.

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8 Revision history

Table 1 summarizes the revisions to this document.

Table 1. Revision history

Revision number	Release date	Description
2	20 November 2023	• Updated Section 6.1.1 • Updated Section 6.1.2 • Updated images to svg files
1	24 May 2022	Replaced LPC553x with LPC553x/LPC55S3x
0	11 January 2022	Initial public release

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