TB3132

Operational Amplifier Module of 8-Bit PIC® Microcontrollers

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INTRODUCTION

The operational amplifier (op amp) is considered the fundamental building block of analog circuits. The two basic functions of an op amp are to perform mathematical operations and to provide amplification to differential input signals, hence the name operational amplifier. It is a versatile and widely used analog circuit implemented in a vast collection of analog as well as a combination of analog and digital applications for signal conditioning and signal processing.

Microchip's 8-bit PIC® microcontroller's OPA module provides all the basic functionalities of an op amp. When integrated with other on-chip intelligent analog peripherals such as the ADC, Comparator, DAC, Fixed Voltage Reference (FVR), Zero Cross Detect (ZCD), Slope Compensator (SC) and Programmable Ramp Generator (PRG), a wide variety of analog applications can be made possible. Furthermore, PIC microcontrollers provide the ease of integrating analog and digital peripherals for a vast range of more complex applications.

This technical brief provides a straightforward discussion on the OPA module's features, DC and AC specifications, modes of operation and sample integration with other peripherals.

OPA MODULE KEY FEATURES

The OPA module is designed to be implemented in single supply op amp circuits with increased flexibility and reliability. The following are the key features of the OPA module of 8-bit PIC microcontrollers:

- External Connections to I/O Ports
- Low Leakage Inputs
- Rail-to-Rail Inputs/Outputs
- Factory Calibrated Input Offset Voltage
- 3 MHz Gain Bandwidth Product (GBWP)
- Unity Gain Control(1)
- Programmable Positive and Negative Source Selections(1)
- Override Controls(1)
  - Forced tri-state output
  - Forced unity gain

Note 1: See Table A-1 for the list of devices that support these features.

OPA MODULE BLOCK DIAGRAM

Figure 1 shows the OPA module block diagram which is divided into five sections. Note that not all sections and features may be supported by all PIC microcontrollers. Hence, the user must refer to the device data sheet for device-specific information.

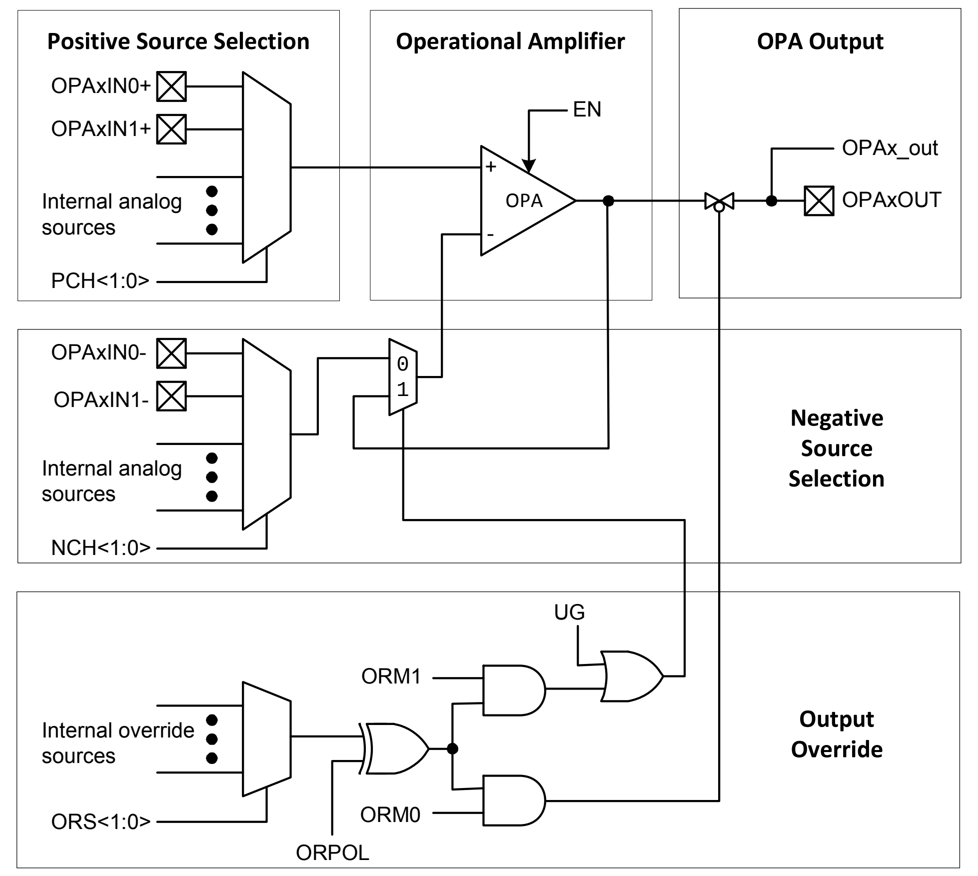
The op amp is a very high-gain electronic amplifier with a differential input and a single-ended output. It has two inputs, namely the non-inverting (+) and inverting (-) inputs. These are referred to as the positive and negative inputs on the device data sheet. Sources for both the positive and negative inputs may vary per device. The inputs may either be taken from external sources through the device pins or from internal analog sources such as the DAC, SC, PRG, FVR and other OPA modules.

Since the op amp is designed to operate with feedback, external feedback components must be connected to the OPA pins depending upon the desired application. These external components predominantly dictate the behavior of the OPA module output. The OPA output can be taken from the device pins and can be fed directly to other on-chip analog peripherals.

The OPA module can also be operated in Unity Gain mode by setting the OPAxUG bit of the OPAxCON register. This allows the inverting input to be internally connected to the output, which also releases the OPAxIN (i.e., pin for general purpose input and output).

Several PIC microcontrollers feature an output override in which the OPA output is forced to tri-state or to behave in Unity Gain mode if the override source is true. These modes can be selected through the ORM<1:0> bits of the OPAxCON register. The ORPOL bit of the OPAxCON register controls the polarity of the override source. Setting this bit to '1' allows the override source to be inverted (override occurs when the source is true), while clearing this bit allows the override source not to be inverted (override occurs when the source is low). Override sources are from other internal peripherals such as the outputs from CCP, PWM, Comparator, ZCD, CLC, and COG. These override sources can be selected through the OPAxORS register.

FIGURE 1: OPA MODULE BLOCK DIAGRAM



OPA SPECIFICATIONS

The OPA module has specifications that must be considered by the designer to ensure proper operation as well as to protect the device from being damaged. These are categorized into DC and AC Specifications and can be found in the Electrical Specifications section of the particular device data sheet.

OPA OPERATION IN THE LINEAR REGION

The range $V_{SS} \leq V_{OUT} \leq V_{DD}$ is often called the linear region of the amplifier. The OPA module features rail-to-rail operation to maximize the full dynamic range of the op amp. Because PIC microcontrollers are designed for single supply operation, V_{SS} is usually tied to ground allowing a maximum voltage output swing of approximately between ‘0’ and V_{DD}.

FIGURE 2: NON-INVERTING OPA

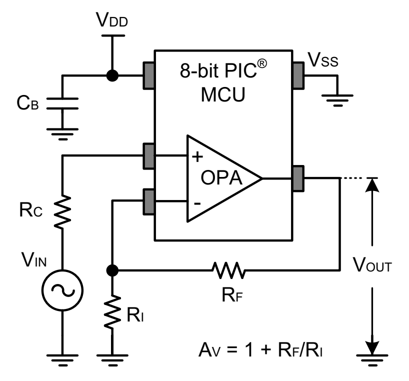
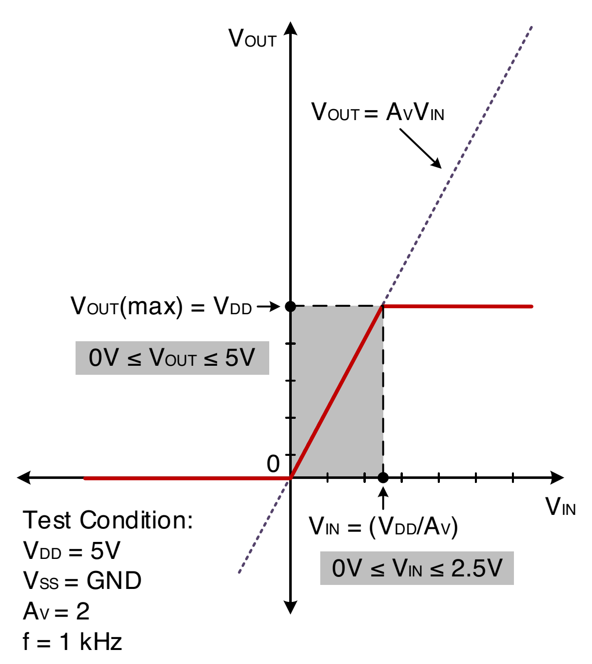


Figure 2 shows the OPA module of an 8-bit PIC microcontroller in a non-inverting configuration. The input signal is fed directly to the non-inverting input of the amplifier. Resistors R_F and R_I determine the Closed Loop Voltage Gain (A_{CL}). C_B acts as a decoupling/ bypass capacitor to reduce the noise in the circuitry. R_C, whose value is equal to the parallel combination of R_F and R_I, is a bias compensating resistor to reduce the effects of bias currents at the input. The transfer characteristic of this op amp configuration is shown in Figure 3.

FIGURE 3: NON-INVERTING OPA TRANSFER CHARACTERISTICS



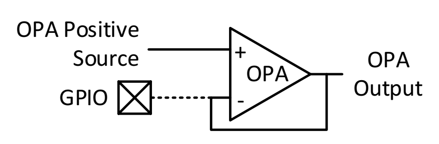
As shown in Figure 3, the OPA module exhibits linear behavior between VDD and '0'. The designer must ensure that the input signal does not go above VDD or below VSS. Otherwise, unexpected behavior of the microcontroller might be encountered. Just like typical op amps, the OPA module can be configured for a wide variety of applications by manipulating the connections of external control elements (e.g., resistors, capacitors, diodes, etc.) Since the OPA module is designed for linear operations, the user must always take note of the electrical specifications and limitations for a more optimized output performance.

OPA IN UNITY GAIN MODE

Some applications only require isolation between subsequent circuit stages due to load impedance variations. This can be achieved by implementing an isolation circuit that does not draw any current from the first circuit but delivers the desired current to the next circuit. This isolation circuit can also be used for power amplification. The same voltage is driven from a lower impedance source but a higher power output can be achieved in the output. An op amp exhibits a very high input impedance and a very low output impedance, which makes it the most practical choice for such applications. The op amp can also be configured so that it does not amplify or attenuate the input signal. This type of op amp circuit is known as the Unity Gain buffer or voltage follower. The Unity Gain buffer is simply a non-inverting amplifier with the output directly connected to the inverting input.

In PIC microcontrollers, the OPA module can be configured in Unity Gain mode without additional external components by setting the OPAxUG bit of the OPACON register. When Unity Gain mode is selected, the OPA output is tied internally to the inverting input. This also releases the inverting input pin as a general purpose input/output pin (see Figure 4).

FIGURE 4: OPA UNITY GAIN CONFIGURATION



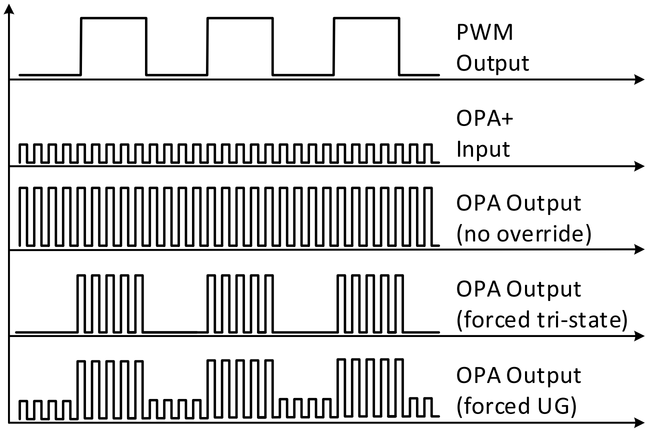
The transfer characteristic of the OPA module in Unity Gain mode is similar to the non-inverting amplifier in Figure 3, but with a gain of '1' or unity. This would mean a fixed 45° slope as long the op amp is operating in its linear region.

OPA OUTPUT OVERRIDE MODE

Several PIC microcontrollers feature an output override mode in which the output pulses from the CCP, PWM, Comparator, ZCD, CLC or COG modules can be used to provide switching control over the OPA output. There are two mode selections for the output override: Forced Tri-state and Forced Unity Gain.

Figure 5 shows sample OPA output waveforms using the PWM module as the override source. The override source is not inverted which means that the override occurs when the PWM output is low.

FIGURE 5: SAMPLE INPUT AND OUTPUT WAVEFORMS



To gain a better understanding on the importance of the output override mode, a sample application is presented in **PWM LED Dimmer Feedback Circuit**.

INTERNALLY-CASCADED OPA MODULES

8-bit PIC microcontrollers, such as the PIC16F1769, allow programmable connection of the output of one OPA to the input of another OPA. These internally-cascaded OPA modules are useful if a very high gain is desired or if there is a need to isolate the op amp output from the load. The output of the cascaded op amps depends mainly on the gain of the individual stages (see Figure 6).

FIGURE 6: CASCADED OP AMP BLOCK DIAGRAM

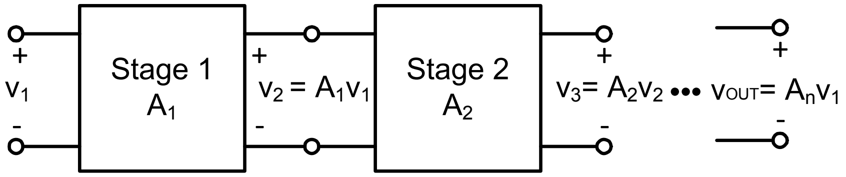
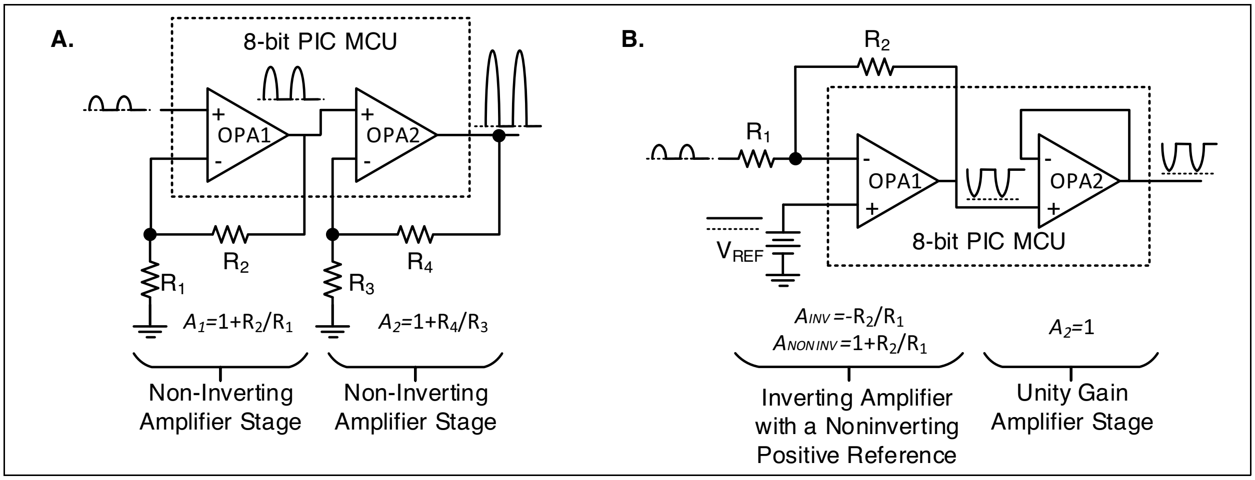


Figure 7 shows two sample circuit configurations implementing internally-cascaded OPA modules. Part A of Figure 7 is made up of two non-inverting amplifier stages to produce a very high-gain output. This configuration is useful for high-frequency circuits due to the inverse relationship between the amplifier gain and frequency below the -3 dB point. Moreover, higher resistance values also result in higher thermal noise generated by the resistors. To eliminate thermal noise while achieving the desired gain, cascading amplifiers would be the best option. On the other hand, part B of Figure 7 is composed of an inverting amplifier with a non-inverting positive reference, which basically produces an amplified difference signal between the inverting input and the reference voltage, and a Unity Gain amplifier which provides isolation between the preceding stage's output and the load to eliminate any loading effects.

FIGURE 7: CASCADED OPA MODULES SAMPLE CONFIGURATION



Cascading OPA modules can be done through firmware by simply setting the output of one OPA module as the negative or positive input of another OPA module.

INTEGRATING THE OPA MODULE WITH OTHER PERIPHERALS

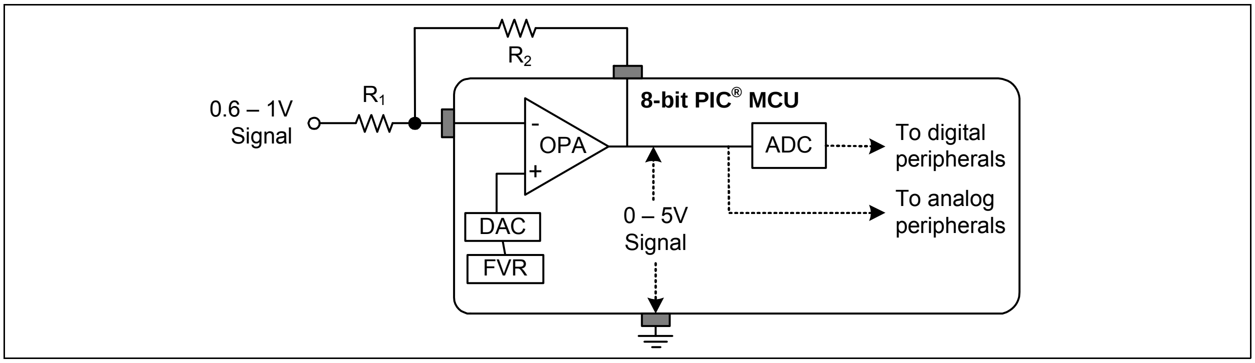
PIC microcontrollers offer ease of integration of the OPA module with other peripherals while reducing the need for external components for a wide variety of applications. To better understand the advantages of using the internal OPA module, two sample applications are briefly presented below.

Basic Signal Conditioning

One of the most common applications of op amps is for signal conditioning in which there is a need to manipulate input signals to meet the requirements of the succeeding stages. Figure 8 shows a basic signal conditioning circuit requiring a signal with an input range of 0.6–1V to be translated to a 0–5V range for an optimized resolution before feeding to the Analog-to-Digital Converter (ADC) module. This circuit performs two functions: scaling and level shifting.

The OPA module is on an inverting configuration, which means that it will output an inverted and amplified replica of the differential input signal. The range of the output signal is dependent on the inverting amplifier's gain. The product of the input signal and the gain determines the scale of the output signal.

FIGURE 8: ADC SIGNAL CONDITIONING



However, the 5V scaled result does not fall exactly on the 0–5V range. Hence, the output voltage needs to be shifted to the desired output level by adding a positive reference voltage on the non-inverting input of the op amp.

The transfer equation for this op amp circuit is expressed in Equation 1.

EQUATION 1: INVERTING OP AMP WITH NON-INVERTING POSITIVE REFERENCE TRANSFER EQUATION

$$V_{OUT} = -V_{IN} \cdot \underbrace{\left(\frac{R_2}{R_1}\right)}_{\text{Scaling}} + \underbrace{V_{REF} \cdot \left(\frac{R_2 + R_1}{R_1}\right)}_{\text{Level Shifting}}$$

The transfer equation expressed in Equation 1 is assumed to be ideal, whereas in reality, certain discrepancies exist due to the tolerance of several components (i.e., resistors). For a more precise output, the reference voltage needs to be varied. To eliminate the use of external voltage sources, the internal Fixed Voltage Reference (FVR) and the Digital-to-Analog Converter (DAC) modules are implemented in this example. The FVR is configured to provide a stable voltage reference to the DAC. The DAC then divides this fixed voltage into 512 software configurable output levels that will serve as the reference to the non-inverting input of the OPA module.

Once the signal has already been scaled and level shifted to the desired output, it is fed to the ADC module for digital processing. The optimized signal from the OPA module results in a significant decrease on the ADC step size yielding a much higher effective resolution as compared to the unconditioned signal. Equation 2 shows the relationship between the ADC step size and the input voltage range. The step sizes for both the conditioned and unconditioned signals in this sample application are shown in Example 1 and Example 2, respectively.

EQUATION 2: RELATIONSHIP BETWEEN ADC STEP SIZE AND INPUT VOLTAGE RANGE

$$ADC\ Step\ Size = \left|\frac{V_{Upper\ Limit} - V_{Lower\ Limit}}{2^n - 1}\right|$$

Note: n = ADC resolution (bits)

EXAMPLE 1: ADC STEP SIZE FOR UNCONDITIONED INPUT SIGNAL

$$ADC\ Step\ Size = \left|\frac{5 - 0}{2^{10} - 1}\right| = 4.88\ mV$$

EXAMPLE 2: ADC STEP SIZE FOR CONDITIONED INPUT SIGNAL

$$ADC\ Step\ Size = \left|\frac{1 - 0.6}{2^{10} - 1}\right| = 0.39\ mV$$

The OPA output can also be fed to other analog peripherals for further analog processing.

PWM LED Dimmer Feedback Circuit

Figure 9 shows a current-mode boost controller for constant-current PWM LED dimming. In this circuit, a boost converter is used to supply constant-current to the series-connected LEDs. Maintaining the current constant from the variation of input voltage and the LED's total resistance is significant to maintain the true color of the LEDs. This current is primarily a function of the Complementary Output Generator (COG) output duty cycle.

The COG output, which is fed to the Data Signal Modulator (DSM), is used to switch power MOSFET Q1 between ON and OFF. Its switching period is determined by the CCP module which serves as the COG rising event source and the comparator module as the falling event source. The CCP is configured in PWM mode to provide a fixed-frequency pulse train whose value typically ranges from 100 kHz to 500 kHz. On the other hand, the comparator is used to produce an output pulse whenever the voltage across RSENSE1 exceeds the output of the PRG module. The PRG, whose input is derived from the output of the OPA module in the feedback circuit, is configured as a slope compensator to counteract the effect of inherent subharmonic oscillations when the duty cycle is greater than 50%.

PWM3 controls the dimming to provide the necessary effective average current to control the LED brightness without affecting its color. It provides a 200 Hz pulse-width modulated output for COG output modulation, load switching and OPA output override. The PWM3 duty cycle dictates the LED dimming ratio, which in turn determines the light intensity of the LEDs. A higher duty cycle ratio means a longer MOSFET Q2 ON time, hence a brighter LED.

When the PWM3 output goes low, the COG output is disabled through the DSM module, Q2 switches off and the OPA output is forced to tri-state. The DSM uses PWM3 as the modulation source to provide synchronized switching with Q2 and the OPA output. It also ensures that the full pulse out of the COG is completed before the output switches to fixed low. Disabling the COG prevents the occurrence of output overvoltage condition, while forcing the OPA to tri-state maintains the steady state LED current.

The OPA module is implemented as an error amplifier with a Type II Compensator configuration in this circuit. The FVR is used as the DAC input to provide a variable voltage reference to the OPA non-inverting input based on the LED constant current specification. On the other hand, RSENSE2, which translates the LED current to voltage, is connected to the OPA inverting input. When Q_2 turns off, the feedback becomes zero and the OPA module increases its output to the maximum, overcharging the compensation network. When PWM3 turns on again, it takes the compensator several switching cycles to recover while a large current peak is driven through the LEDs. This scenario often causes the LED current to overshoot which contributes to a shorter LED life time. In this sample application, the OPA module is configured with the PWM3 as the override source and the output is tri-stated when the PWM output is low. Figure 10 summarizes the advantages of simultaneous switching of PWM3 and the OPA output to alleviate LED current overshoot and color shifting.

FIGURE 9: CONSTANT CURRENT PWM LED DIMMING CIRCUIT

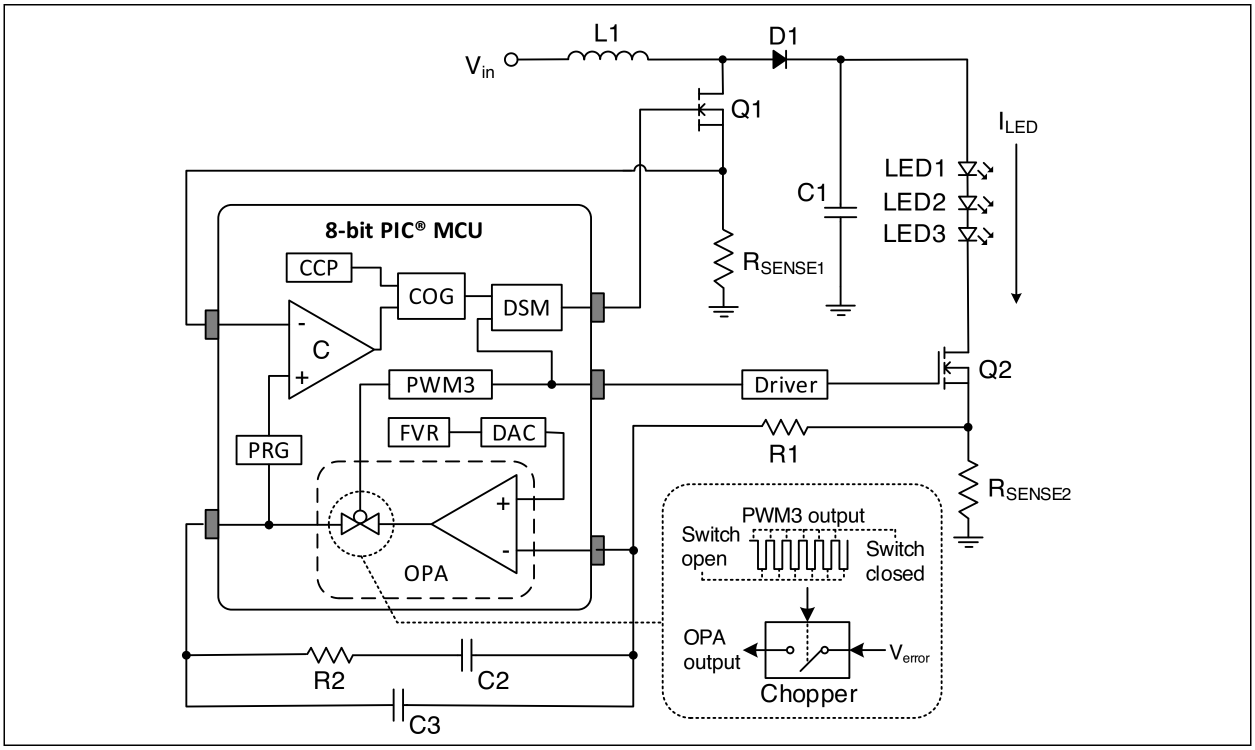
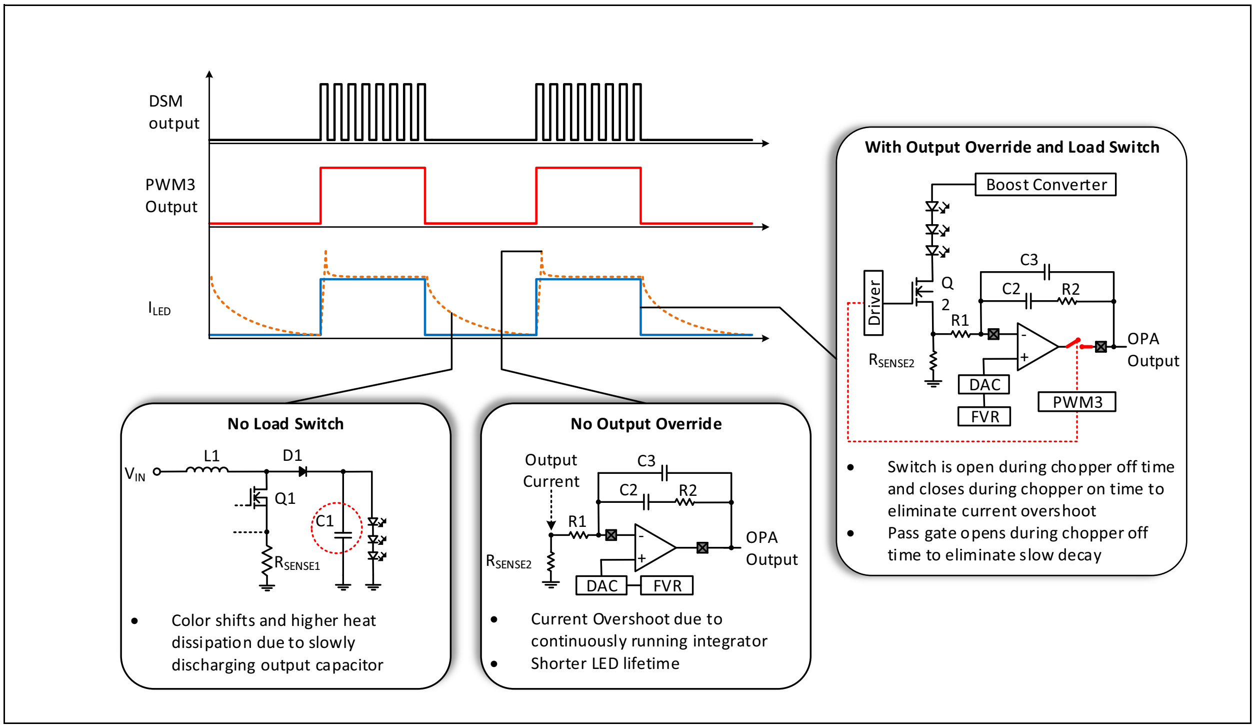


FIGURE 10: EFFECTS OF OPA OUTPUT OVERRIDE ON LED DIMMING



No Load Switch

- Color shifts and higher heat dissipation due to slowly discharging output capacitor

No Output Override

- Current Overshoot due to continuously running integrator
- Shorter LED lifetime

With Output Override and Load Switch

- Switch is open during chopper off time and closes during chopper on time to eliminate current overshoot
- Pass gate opens during chopper off time to eliminate slow decay

CONCLUSION

The OPA module of 8-bit PIC microcontrollers provides not only the basic functionalities of single supply op amps, but also exhibits more enhanced features for maximum flexibility in op amp circuit designs. At present, as portable equipment are becoming more popular, single supply op amp circuits are also becoming more in-demand. Integrating the OPA module with other on-chip analog peripherals provides the advantage of lower production costs, reduced board space, and more efficient circuit performance for a variety of applications.

ADDITIONAL REFERENCES

1. *AN722 Operational Amplifier Topologies and DC Specifications* (DS00722)
2. *AN723 Operational Amplifier AC Specifications and Applications* (DS00723)
3. *AN1747 Operational Amplifier Applications using 8-bit PIC® Microcontrollers* (DS00001747)

APPENDIX A: OPA MODULE FEATURES OF 8-BIT PIC® MICROCONTROLLERS

TABLE A-1: OPA MODULE FEATURES SUMMARY TABLE

8-bit PIC® MCU	No. of OPA	Internal Input Connections to					Internal Unity Gain Bandwidth Mode Selection	Output Override Source Selection
		DAC	FVR	SC	PRG	Other OPA		
PIC16F527	2	—	—	—	—	—	—	—
PIC16F570	2	—	—	—	—	—	—	—
PIC16F753	1	✓	✓	✓	—	—	✓	—
PIC16F785	2	—	—	—	—	—	—	—
PIC16F1703	2	—	✓	—	—	—	✓	—
PIC16F1704	2	✓	✓	—	—	—	✓	—
PIC16F1705	2	✓	✓	—	—	—	✓	—
PIC16F1707	2	—	✓	—	—	—	✓	—
PIC16F1708	2	✓	✓	—	—	—	✓	—
PIC16F1709	2	✓	✓	—	—	—	✓	—
PIC16F1713	2	✓	✓	—	—	—	✓	—
PIC16F1716	2	✓	✓	—	—	—	✓	—
PIC16F1717	2	✓	✓	—	—	—	✓	—
PIC16F1718	2	✓	✓	—	—	—	✓	—
PIC16F1719	2	✓	✓	—	—	—	✓	—
PIC16F1764	1	✓	✓	—	✓	—	✓	✓
PIC16F1765	1	✓	✓	—	✓	—	✓	✓
PIC16F1768	2	✓	✓	—	✓	✓	✓	✓
PIC16F1769	2	✓	✓	—	✓	✓	✓	✓
PIC16F1782	2	✓	✓	—	—	—	—	—
PIC16F1783	2	✓	✓	—	—	—	—	—
PIC16F1784	3	✓	✓	—	—	—	—	—
PIC16F1786	2	✓	✓	—	—	—	—	—
PIC16F1787	3	✓	✓	—	—	—	—	—
PIC16F1788	2	✓	✓	—	—	—	—	—
PIC16F1789	3	✓	✓	—	—	—	—	—

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