

LMP91051 NDIR CO₂ Gas Detection System

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1 Abstract

This Application Note begins with an introduction to nondispersive infrared (NDIR) gas sensing. The use of the LMP91051 NDIR AFE and MSP430F55XX microcontroller to make accurate CO₂ NDIR gas measurements is examined. Performance, power, speed, and size are compared against the traditional discrete op amp system.

2 NDIR Gas Sensing Principle

NDIR technology, a type of IR spectroscopy, is based on the principle that gas molecules absorb IR light and absorption of a certain gas occurs at a specific wavelength. Typically, a thermopile with a built-in filter is used to detect the amount of a specific gas. For instance, since CO₂ has a strong absorbance at a wavelength of 4.26 μm, a band-pass filter is used to remove all light outside of this wavelength. Figure below shows the basic NDIR gas sensor working principle.

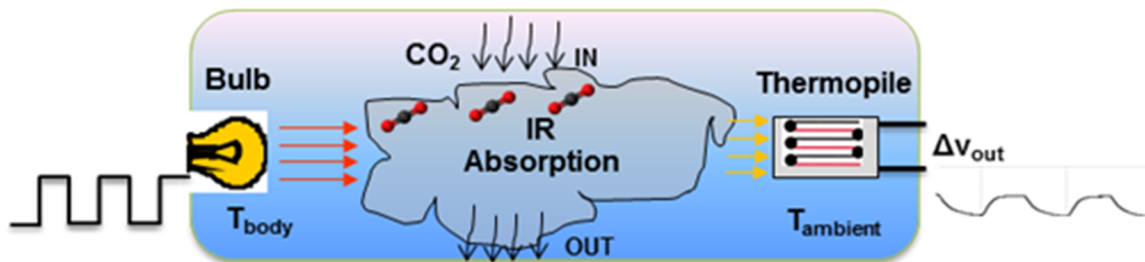


Figure 1. NDIR Gas Sensor Principle

Gas molecules will absorb radiation energy from the lamp emission. Absorption follows the Lambert-Beer law:

$$I = I_0 * e^{-kcl}$$

Where I is the transmitted IR intensity at the thermopile detector side, I_0 is the initial intensity at the IR source, k is the gas specific absorption coefficient of the target gas, c is the gas concentration, and l is the length of the absorption path from light source to thermopile detector.

The thermopile is used to detect the light intensity change. Its output voltage will follow:

$$V = n * \Delta\alpha * (T_{body} - T_{amb})$$

Where $\Delta\alpha$ is the difference of the Seebeck coefficients of the thermopile materials and n is the number of thermocouples in thermopile detector. T_{body} is the blackbody temperature that is emitting thermal radiation (i.e. the IR lamp), and T_{amb} is the temperature of the surrounding ambient.

Inside the gas chamber, the IR lamp radiation energy could be regarded as ideal black body radiation. The radiation emitted by a blackbody as a result of the temperature difference between the blackbody and ambient is known as thermal radiation. According to Stefan-Boltzmann law, thermal radiation per unit area is expressed with the following equation:

$$R_T = \sigma * (T_{body}^4 - T_{amb}^4)$$

where $\sigma = 5.67 * 10^{-8} \text{ W}/(\text{m}^2 * \text{K}^4)$ is the Stefan-Boltzmann constant.

Assuming no loss in light intensity while traveling through the chamber, then $R_T = I$. After rearranging the equations above the equation for thermopile output voltage becomes:

$$V = n * \Delta\alpha * [I_0 * e^{-kcl}] / [\sigma * (T_{body}^2 + T_{amb}^2) * (T_{body} + T_{amb})]$$

If we examine this equation it makes sense that the thermopile output voltage will be affected by the ambient temperature and the IR lamp intensity uncertainty with a complex relationship. In order to maintain better accuracy of the system, special consideration should be taken in the design implementation. We can see that temperature compensation is an effective way to maintain system accuracy. To accomplish this thermistors are commonly integrated into the thermopile sensor and their resistance changes depending on the surrounding ambient temperature. For better measurement accuracy, having a stable constant voltage to excite the thermistor is a good choice.

3 Traditional Discrete Op Amp Signal Conditioning

Traditionally discrete op amps have been employed for the gain stage of NDIR systems. AC coupling is required in order to eliminate the signal chain offset. To handle a two channel system one could use a quad op amp configured in a dual channel 2 stage front end. Active filtering is built into the signal path.

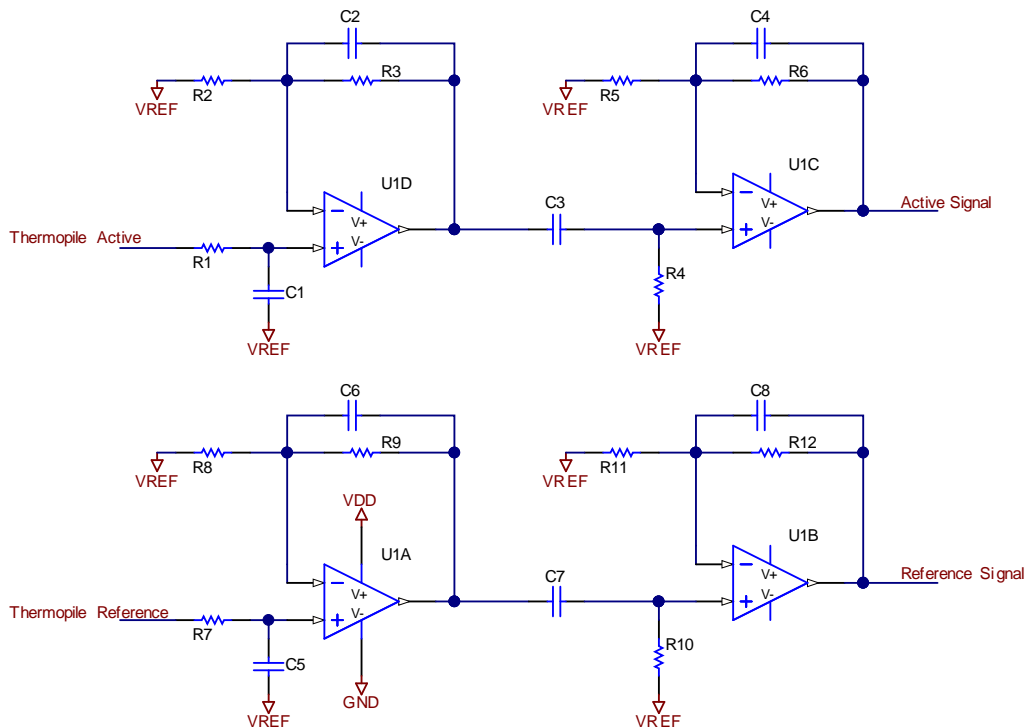


Figure 2. Discrete Op Amp Based System

4 LMP91051 Sensor AFE for NDIR Gas Sensing

An integrated analog front-end (AFE) can save design time and complexity by incorporating the features of a discrete op amp solution into one chip. The LMP91051 AFE contains a two channel PGA which allows easy interface to a two channel NDIR sensor. By cancelling out errors due to light source deviation optimum accuracy is obtained in a two channel system. This deviation results in long-term drift, which occurs over large periods of time. Hence, the requirement to simultaneously sample both the reference and active channel simultaneously is not required. You can use the input multiplexer (MUX) to switch between the two channels, reducing system cost and complexity, while maintaining accuracy.

The LMP91051 also has fully programmable gain and offset adjustment. This helps ensure that the small thermopile output (100's μV) is matched to the dynamic range of the sampling Analog to Digital converter (A/D) and improves system resolution. The LMP91051 also provides a common mode bias which level-shifts the thermopile sensor signal away from the negative rail, allowing for accurate sensing in the presence of sensor offset voltages.

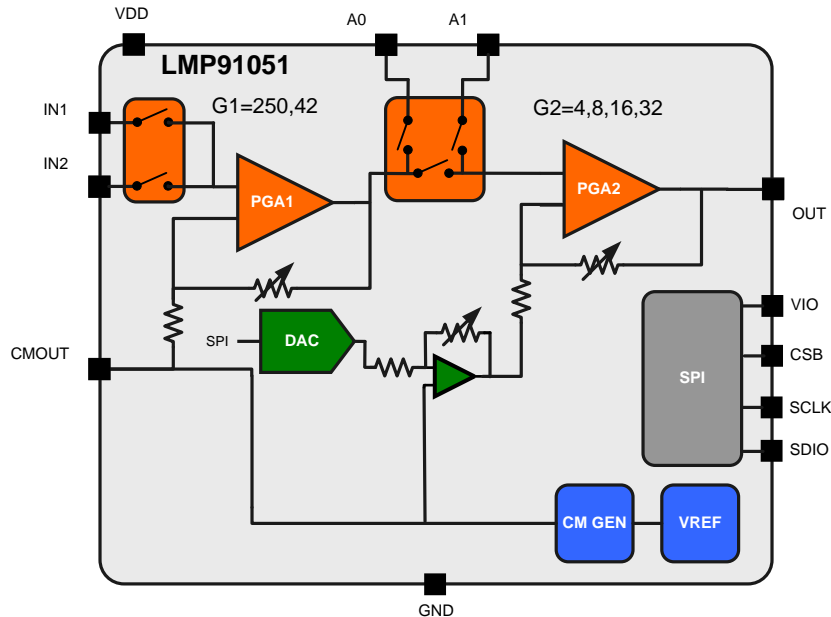


Figure 3. LMP91051 Sensor AFE for NDIR Sensing

5 LMP91051 Gas Detection System

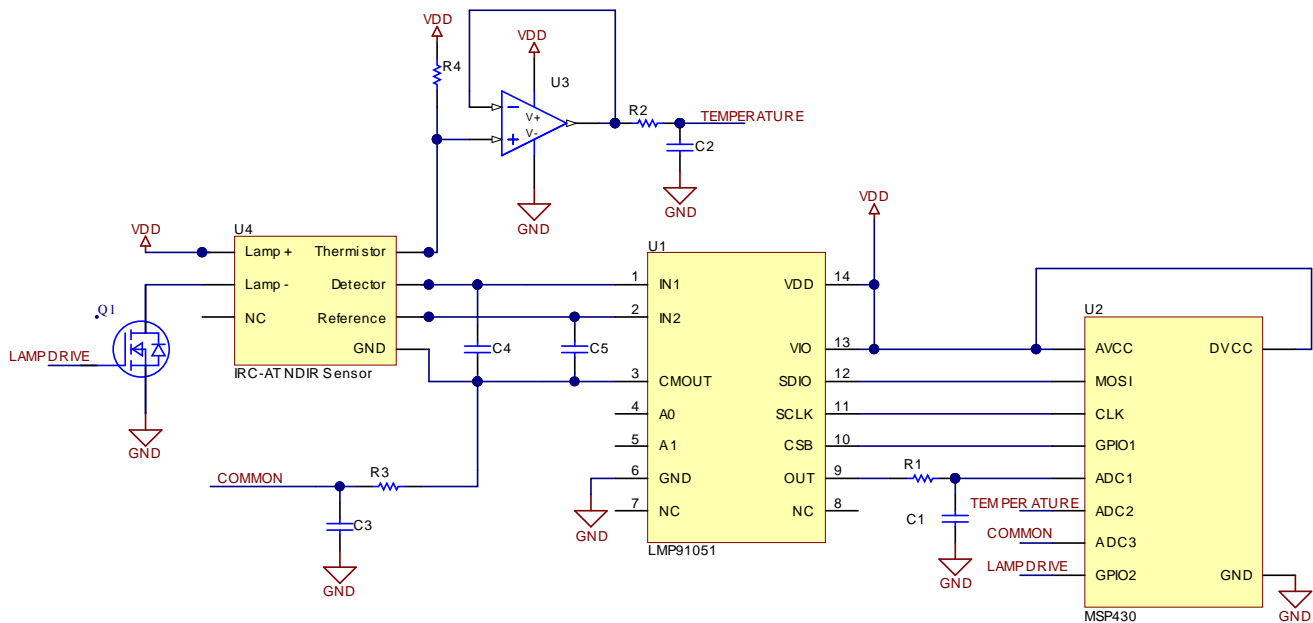


Figure 4. LMP91051 CO2 Gas Detection System

The NDIR sensor used in the proposed system is a Alphasense IRC-AT. The sensor is composed of an IR lamp, two thermopile channels, and a thermistor which is used for temperature calibration. To save power and to avoid overheating the device the lamp source is modulated typically with a 50% duty cycle with a frequency of 1 to 3Hz. The Detector (Active) and Reference channel output are connected directly to the inputs of the LMP91051. Filter capacitors are connected from each input to the common mode reference, CMOUT, to provide low pass filtering. LMP91051 external filtering option is disabled and pins A0 and A1 are shorted internally in the chip. No high pass filtering (AC coupling) is required because the internal offset DAC is used to cancel offset error in the signal chain. This facilitates faster measurements over the traditional AC coupled system which will be discussed further later in this application note. The NDIR sensor has an internal thermistor which is connected to a resistor bridge then buffered by an amplifier.

The MSP430 microcontroller programs the LMP91051 via SPI. The microcontroller utilizes an internal 12 bit muxed A/D to sample the LMP91051 output, buffered thermistor output, and system common mode. The entire system can be powered off of a single supply of 3V.

6 Gas Detection Method and Settings

In a 2 channel NDIR system the integrated IR lamp is pulsed (typical 1 to 3Hz) with a 50% duty cycle resulting in small 100's uV RC waveforms seen on both the output of the active and reference channel. To improve measurement accuracy these signals are amplified and the peak to peak waveform voltage of both the active channel and reference channel are compared. In a DC coupled single supply system, active DC offset adjustment is required in order to ensure the output of the gain stage doesn't saturate and to remove signal chain offset errors.

In a Muxed 2 channel system toggling between channels is done at an increased rate (i.e 100Hz) in order to reliably reconstruct both channels. To ensure accurate sampling, multiple samples should be taken on each channel prior to switching channels. Preferably sampling is synced to the lamp pulses to ensure data is being capture at the expected time relative to the lamp switching and the same sample within one lamp cycle can be looked at over many lamp cycles to determine noise performance. Figure below provides a visual explanation of the proposed gas detection method.

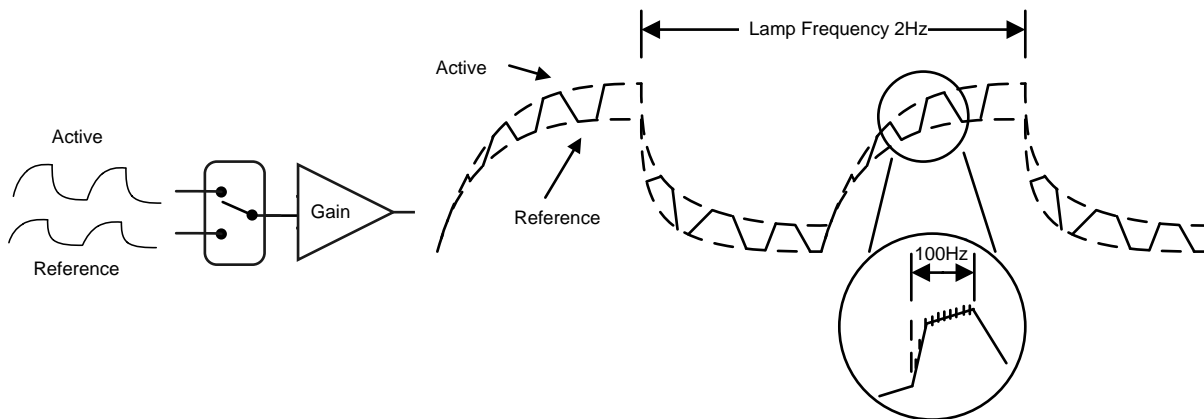


Figure 5. Example Gas Detection Method

The system that was constructed and verified in the lab had the following settings. Image below shows actual system RC waveform as measured in the lab.

Lamp Pulse Frequency: 2 Hz

System Gain: 2000 V/V

System Offset: Apx. -700mV

Input Channel Mux Toggle Frequency: 100Hz

Number of Ch. Samples per Ch. Toggle: 10

ADC Sampling Rate: 1ksps

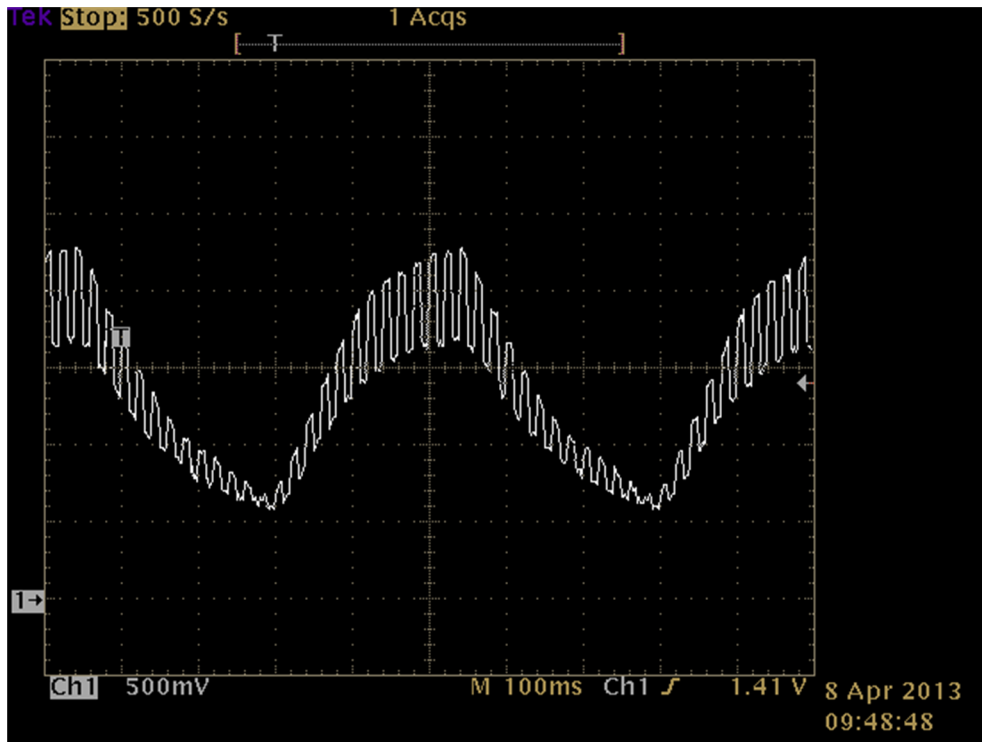


Figure 6. System Waveform

7 Performance

Functionality of the LMP91051 based system was demonstrated over CO₂ concentration, lamp frequency, signal path gains, and offsets. Thermopiles used in NDIR sensing have a relatively high internal resistance (~100 kohm) and 50/60Hz power main noise can couple into the signal path and become noticeable in this high gain application. Noise will be present in the signal path in a DC coupled system without filtering. To minimize noise low pass filtering should be added or averaging (filtering) can be performed in the digital domain. The tradeoff is that if the cut off frequency is too low the sensor signal may not have enough time to completely settle.

A way to limit wide band noise is to create a low pass filter with the inherent source impedance of the NDIR thermopile. The thermopile sensors themselves can have a source impedance up to 100 kohms and their thermal noise can dominate the system noise. Placing capacitors from the sensor outputs to system common mode will form a RC low pass filter minimizing the effects of this noise. In our verified 2Hz lamp frequency system with a thermopile source impedance of 85kohm, a 6Hz low pass filter was formed:

$$F_c = 1/(2\pi * R * C) = 1/(2\pi * 85\text{kohm} * 0.33\mu\text{F}) \sim 6\text{Hz}$$

It is also important to note the lamp biasing potential effect on system accuracy. The incandescent light bulb is glowing when current flows through the filament. Emission light intensity depends on the lamp bias voltage (input power), and in turn the light intensity will effect the thermopile output voltage. That is why a constant and stable light intensity is desired over the entire sensor lifetime. A regulated and clean power supply is a key point to maintain constant light emission.

To determine the span, resolution, and noise performance of the system the following measurements and calculations were made. PGA output was captured with a 12 bit A/D with a voltage reference of 3V. A 6Hz low pass filter was used as described above.

Span

To determine system span, measurements were taken with a low CO₂ concentration of 130 ppm and alternatively with a high CO₂ concentration of 5000 ppm.

CO2 130 ppm: Active Vpp – Reference Vpp = 535mV

CO2 5000 ppm: Active Vpp – Reference Vpp = 275mV

Resulting in a slope of -0.0534mV/ppm or -18.7ppm/mV.

Resolution

Compare the system slope with the LSB of the system to determine system resolution:

$$\text{System LSB} = VREF/2^n = 3V/2^{12} = 0.73mV$$

$$\text{System resolution} = \text{System LSB} * \text{Slope} = 0.73mV/LSB * 18.7ppm/mV \sim 14ppm/LSB$$

Noise

Noise was measured at ambient CO2 concentration of approximately 400ppm. Same sample within one lamp cycle was looked at over multiple lamp cycles to determine noise performance. Approximately 2mVpp of noise was observed. In our 0.73mV/LSB system that results in:

$$\text{System noise} = \text{System Noise} * \text{Slope} = 2mVpp * 18.7ppm/mV \sim 37ppm$$

In summary, using a 12 bit A/D less than 50 ppm/LSB performance was demonstrated. For reference an example off the shelf 0 to 5000ppm sensor may specify +/-50ppm accuracy. In this particular experiment, increasing the LMP91051 programmable gain can improve the system resolution. Note however that the LMP91051 DAC offset will need to be adjusted during lamp cycling in order to avoid saturating the gain stage.

Potential benefits of increasing the A/D resolution can be examined. Performance was demonstrated while using a 12 bit A/D. System resolution of 0.73mV/LSB is already below the noise floor of the system, 2mV/LSB. Therefore by increasing the resolution of the A/D, the performance of the system won't be improved. For example with a 16 bit A/D the added bits of resolution would be lost in the noise of the system.

$$\text{System LSB} = VREF/2^n = 3V/2^{16} = 0.05mV \ll 2mV$$

8 Power

The IR lamp is the main power consumption source in the system. The lamp used for these measurements when on and biased at 3V consumes ~50mA of current. Most power savings will come from the ability to limit the time the lamp is on or in other words limit the number of lamp cycles.

The LMP91051 has a programmable offset DAC that cancels DC errors and allows it to be used in a DC coupled system. A DC coupled system is capable of capturing valid data after 2 cycles (i.e. 1 second w/ 2Hz lamp) vs. the 8 seconds it would take for an AC coupled 0.1Hz high pass system to stabilize and begin taking accurate measurements. Startup comparison in figure below shows DC Coupled System (Purple) settling within ~ 2 cycles whereas AC Coupled System (Green) has not settled after +9 cycles. Valid data in both systems is limited by sensor warm up time. In remote node power critical applications the system is typically powered off, then is powered on for only a brief time to take measurements. The 1 second vs. 8 second advantage can result in as much as 1/8 power consumption savings.

Further power savings is achieved in the LMP91051 system with the integration of the A/D into the microcontroller. For example power required to support an external multi-channel A/D is often greater than 1mA.

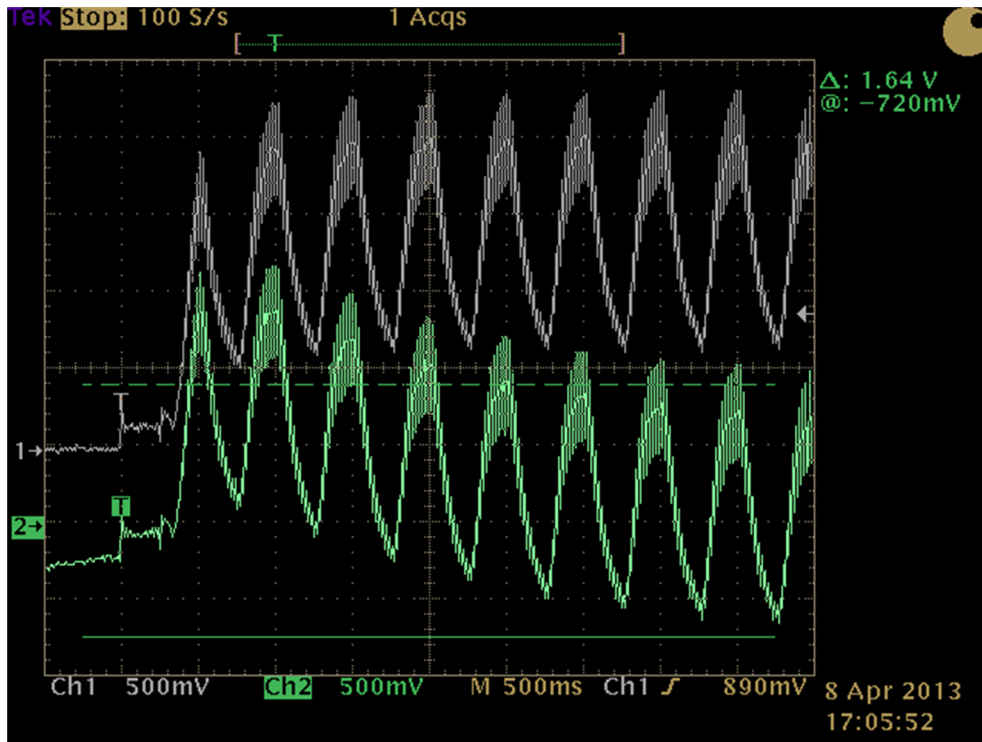


Figure 7. Startup comparison DC Coupled (Purple) vs. AC Coupled (Green) System

9 Speed

2Hz performance has been verified on the tested system. 2 cycle, or 1 second, startup is possible in the LMP91051 DC coupled system. For an AC coupled system with at 0.1Hz high pass filter it could take up to 8 seconds for the input to settle to a stable value. After settling the AC coupled discrete Op Amp solution and DC coupled LMP91051 solution would have comparable speeds set by the lamp frequency.

10 Size

A discrete system utilizing a Quad Op Amp would need passives for filtering, gain, and common mode bias on 2 channels each with 2 gain stages. This can result in over 25mm² of extra board space over the LMP91051 based solution even when using small 0603 components.

Further size savings is achieved in the LMP91051 system with the integration of the A/D into the microcontroller. For example, space required to support an external multi-channel A/D can be up to 5 x 4 mm or 20mm².

11 Conclusion

The LMP91051 when coupled with an MSP430 has been demonstrated to be an accurate, low power, fast speed, and small size alternative to the traditional discrete op amp system.

12 References

"Temperature Compensation of Novel NDIR CO₂ Gas Sensor", SeungHwan Yi, JongSeon Park, and JeongMin Park, IEEE SENSORS 2006, October 2006.

Download these datasheets: [LMP91051](#), [MSP430F5528](#)

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